Universal Optical Logic Gates on a Programmable Silicon Photonic Platform

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Abstract: We propose and demonstrate the implementation of NOT, OR/NOR, and AND/NAND logic gates compatible with integrated photonics. Using a programmable photonic platform consisting of a Mach-Zehnder interferometer mesh, universal logic gates are experimentally demonstrated.

1. Introduction

Optical computing, originally introduced decades ago, has become a promising path to address some of the challenges with all-electronic approaches such as limited computation speed and energy efficiency due to limited clock frequency and power hungry data transfer and conversion. Large available bandwidth at optical frequencies, low-loss transmission, and wavelength/spatial/modal parallelism, can significantly enhance the energy efficiency and processing throughput of computing systems. In addition, significant progress in integrated photonic platforms such as silicon photonics, has enabled low-cost, small-sized, and scalable systems for different applications. Therefore, optical computing can complement the existing electronic systems.

Logic operations are the building blocks of every digital signal processing algorithm, hence, realizing optical logic gates (OLGs) with optical input(s) and optical output(s) enables a wide variety of functionalities in optical signal processing. Basic logic gates typically take one or two inputs and perform a nonlinear operation to generate the corresponding logic output. In electronics, transistors are used to realize this nonlinearity very efficiently. However, due to the lack of an optical transistor, other nonlinear mechanisms have been proposed to realize OLGs. These include nonlinear optical materials such as periodically-poled lithium niobate [1], semiconductor optical amplifiers [2, 3], polarization sensitive nano-wire structures [4], optical absorption modulators based on self electro-optic effect [5], and III-V photonic crystals [6], to name a few. Despite impressive demonstrations, these systems typically require complex bench-top setups and/or materials that are not compatible with scalable integrated photonic platforms such as silicon photonics.

Here we report the implementation of multiple OLGs, namely *NOT*, *OR/NOR*, and *AND/NAND* gates, that leverage the nonlinear electro-optic response of micro-ring modulators (MRMs) and are compatible with any integrated photonic platform that offers modulators and photodetectors (PDs). As a proof of concept, iPronics Smartlight Processor [7], a programmable silicon photonic platform, is used to experimentally demonstrate logic *NOR* and *NAND* operations as universal logic gates.

2. Universal Photonic Logic Gate Architectures

It has been shown that either *NOR* or *NAND* gate is sufficient to reproduce other logic operations. Hence, they are named universal gates and in this work, we focus on universal photonic logic gates by implementing an *OR*/*AND* gate followed by a *NOT* gate.

2.1. NOT Gate

Figure 1a shows the implementation of a *NOT* gate using a MRM. All optical signals have the same wavelength of λ_0. The input optical signal (*IN*) is coupled to a PD. The photocurrent drives the MRM after a limiting amplifier (LA) stage (*i.e.*, V_{in}). The MRM is initially biased at its resonance wavelength λ_{res}, then thermally tuned to reach peak transmission (Fig. 1a bottom). A supply light is coupled to the MRM. For logic level '0' ('1'), *i.e.*, low (high) *IN*, V_{in} is small (large) resulting in high (low) transmission of the MRM, that inverts the input optical logic. Note that the output levels of the limiting amplifier (LA) are designed such that high V_{in} aligns λ_{res} with λ_0.

2.2. OR/NOR Gate

Conceptually, an *OR* operation is equivalent to finding the maximum of the two logic inputs. The output is '0' if both inputs are '0', and is '1' otherwise. This is similar to a max-pooling function that was experimentally shown

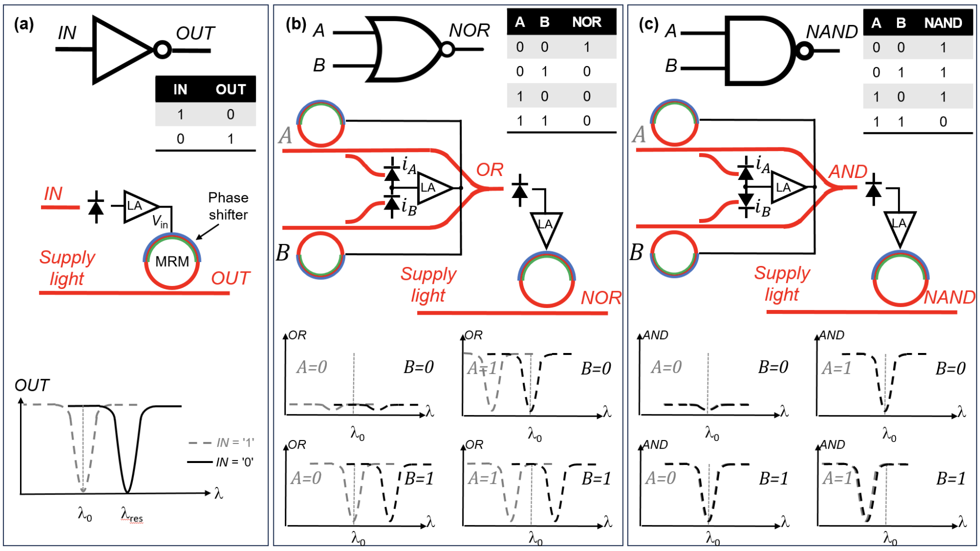

Fig. 1. Photonic implementation and MRM biasing of (a) *NOT* (b) *OR*/*NOR* (c) *AND*/*NAND* gates.

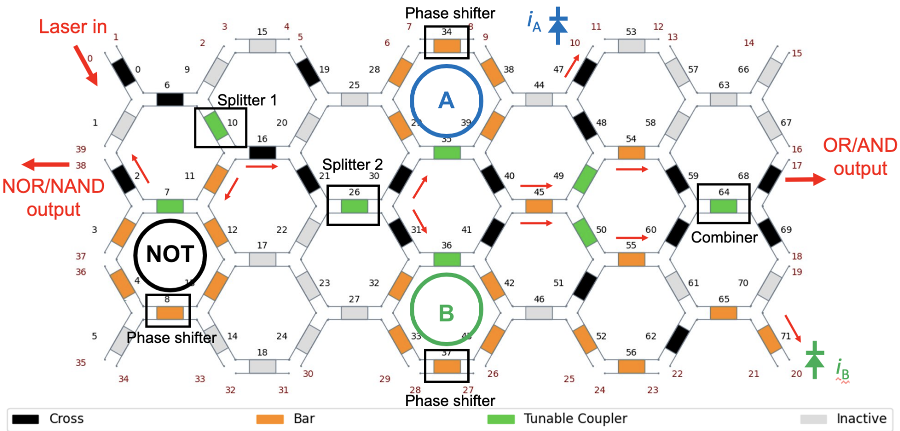

Fig. 2. Implementation of the logic gates in Fig. 1 on a programmable photonics platform. Red arrows show the direction of propagation.

in a prior work [8]. In the circuit in Fig. 1b, A and B are the inputs to the gate and their corresponding MRMs are symmetrically biased around λ_0. Directional couplers tap off a small fraction of A and B after each ring, generating $i_{diff} = i_A - i_B$ using a balanced detector, where i_A and i_B are the photocurrent corresponding to signals A and B, respectively. The amplified i_{diff} drives the MRMs. If $A > B$ ($A < B$), hence $i_{diff} > 0$ ($i_{diff} < 0$), both rings shift to a shorter (longer) wavelength to further attenuate B (A), transmitting the maximum of the two to the output. If both inputs are high, rings do not shift and output maintains a high level. The *NOT* gate in Fig. 1a can then be used to inverts the *OR* output, realizing a *NOR* function (Fig. 2b).

2.3. AND/NAND Gate

An *AND* operation is equivalent to finding the minimum of the two inputs. The output is '1' when both inputs are '1', and is '0' otherwise. As shown in Fig. 1c, input MRMs are initially biased such that their resonance wavelengths are aliened with λ_0. In this case, an LA amplifies $i_{sum} = i_A + i_B$, driving the MRMs. The LA threshold is set such that it generate a high output only when both A and B are '1' (i_{sum} larger than a threshold). Similar to *NOR*, a *NOT* gate after the *AND* output results in a *NAND* operation.

3. Experimental Results

As a proof of concept, the architectures in Fig. 1 are implemented on iPronics Smartlight Processor, a programmable silicon photonics platform. It consists of a hexagonal mesh of Mach-Zehnder interferometers (MZI)

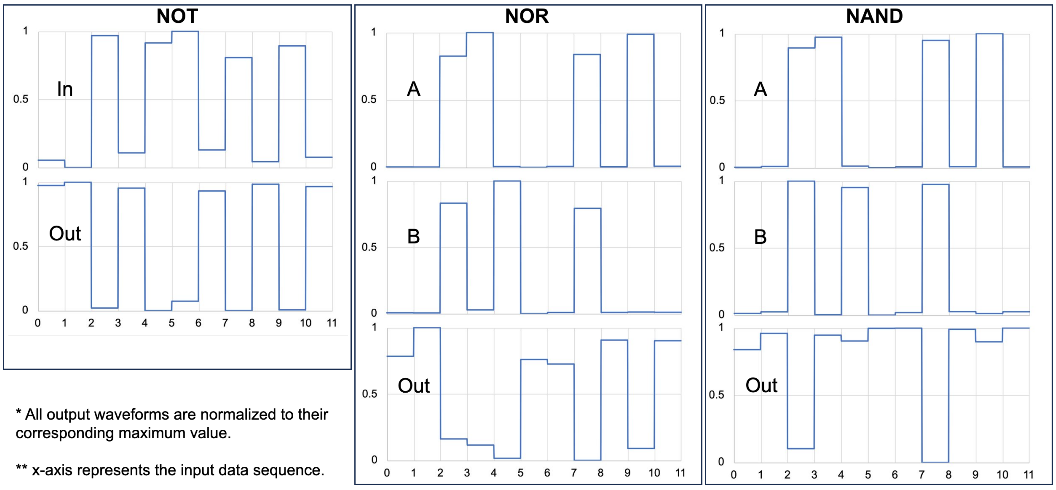

Fig. 3. Experimental results of universal logic gate circuits in Fig. 1 implemented on a programmable photonic platform shown in Fig. 2.

where each MZI can be independently programmed to a cross, bar, or tunable couplers state by adjusting its thermal phase shifters. Note that the proposed architectures can be implemented in any integrated photonic platform that offers phase modulators and PDs. Figure 2 shows the programmed MZI mesh to implement the circuits in Fig. 1a to 1c. The optical input is split into three signals using splitters 1 and 2 as tunable couplers to generate *A*, *B*, and the supply light to the *NOT* gate. Three MRMs are formed and within each, one MZI is used as a phase shifter to tune the resonance wavelength. After rings *A* and *B*, 5% of the optical power is tapped off and photo-detected to generate the feedback signals that drive the MRMs. The circuit generates *OR*/*AND* as well as *NOR*/*NAND* optical outputs using the *NOT* gate.

Figure 3 shows the experimental results corresponding to each gate. In each case, a sequence of 11 random input data points with deliberate amplitude variations is generated by properly programming splitters 1 and 2. In all three cases, correct logic outputs are generated. Note that despite the variations of the inputs, the output logic levels can clearly be distinguished. Although iPronics platform uses thermal phase shifters, the same gate architectures can be implemented using fast (*e.g.*, PN) modulators and PDs to achieve picosecond response times.

4. Summary and Conclusion

In this work, we proposed architectures to implement universal photonic logic gates (*NOR*, *NAND*) that are compatible with integrated photonic platforms. The optical-in optical-out architectures benefit from the nonlinear electro-optic response of ring modulators to realize various logic functions. As a proof of concept, we experimentally validated the universal logic gate functions using a programmable photonic platform. Logic operations with more number of inputs can be implemented by cascading and forming arrays of such gates. Moreover, using fast modulators and PDs, picosecond response times can be achieved.

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