

2 to 4 Digital Optical Line Decoder based on Photonic Micro-Ring Resonators

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Abstract—The need for the research breakthrough in terms of the underlying electronic components have been rising due to the limitations of the current technology. Several alternative methods for digital circuits are needed, thus silicon photonics could be the answer. This paper presents the design of a digital 2 to 4 electro-optic line decoder based on the photonic micro-ring resonator as its core component. This work provides the design principle of the proposed digital decoder, together with the demonstration and simulation of the time varying operation with the speed of 5Gbps. The performance of the proposed line decoder is shown by clear output timing diagrams.

Keywords—micro-ring resonator; electro-optic devices; combinational logic circuit

I. INTRODUCTION

Optical communication has become one of the key factors towards the ultra-high-speed digital data transmission for future CPUs, due to its lower bit error than the current electronic systems [1-3]. The advancement in electrical communications is currently at the threshold where limited bandwidth is observed, forcing the manufacturers to produce multi-core CPUs that is widely used nowadays [4-6]. Due to the flat channel loss over a wide range of optical frequencies, with little crosstalk and electromagnetic interference, optical communication channels are used instead [7]. Photonic integrated circuit (PIC) have the potential as the new core component inside any CPU due to its micro-scale and low power consumption. Photonic circuits nowadays can be fabricated in CMOS technology [8] allowing the use of electronic fabrication facilities to design and produce photonic circuitry.

Silicon photonic devices have undergone research advancement due to the dedicated research and experimentation that have been carried out. These include the production of silicon-on-insulator (SOI) based slot waveguides with higher quality factor output [9, 10] and high compact silicon photonic crystals for optical switching [11]. Two major photonic devices that are currently undergoing extensive research are the photonic micro-ring resonators and Mach Zehnder Interferometers. We have seen tunable Fano resonance by utilizing the interference of two resonance cavities with different wavelengths [12], and also high-order micro-ring resonators up to 11 coupled cavities are demonstrated to be as filters for WDM applications. We have also researched on the effect of resonance cavities when the micro-ring resonator is modulated by electrical signals [13].

Mach-Zehnder Interferometer researches include a long period grating (LPG) Mach-Zehnder Interferometer used for a low cost, high sensitivity refractometer [14] and also the construction of the interferometer using photonic band gap crystals [15].

We have seen and achieved breakthroughs in terms of using photonic devices, particularly silicon micro-ring resonators, to design several photonic logic gates and circuits, such as the photonic logic NOR gate based on two micro-ring resonators [16], as well as the design and simulation of a digital photonic half adder using micro-ring resonators [17]. We hope to design more of digital logic circuits based on silicon micro-ring resonators to achieve more electro-optic logic circuits as part of a future generation computing technology.

This paper details the design of a digital 2 to 4 line decoder using the nonlinear resonance shifting property of a micro-ring resonator as its base element. The paper also demonstrates time varying simulations of a data rate of 5Gbps with timing waveforms to justify its mode operation.

II. PRINCIPAL DESIGN OF 2 TO 4 LINE DECODER

The general 2 to 4 line decoder uses four digital logic AND gates as well as two digital inverter for its logic circuit as shown in Fig 1 [18], with its truth table being shown in Table 1. The principal objective of our proposed design is to replace those AND gates as well as the inverters with our designed silicon micro-ring resonators operating as the desired logical mode operation, thus creating our proposed digital electro-optic line decoder design.

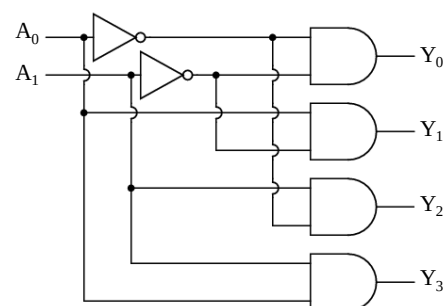


Fig. 1. Generic 2 to 4 line decoder circuit design.

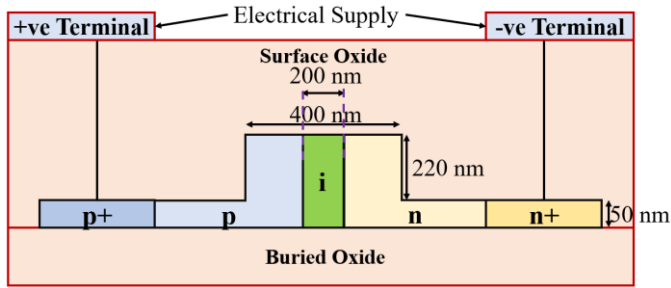


Fig. 2. Silicon PIN ring waveguide cross section.

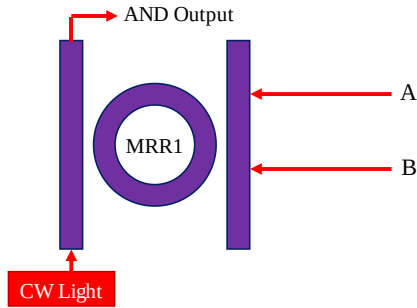


Fig. 3. Schematic setup of the microring resonator as a digital logic AND. Modulation voltage signals for both A and B have the amplitude of 0.6V.

The silicon micro-ring resonator we used incorporates a ring waveguide with its cross-section as shown in Fig. 2 while the ring resonator itself is designed to follow its properties as shown in Table 2. The waveguide is placed on top of a 1- μm thick buried SiO_2 layer, where the waveguide itself is silicon based with thickness of 270nm. The waveguide's core is designed with the dimension of 400nm in width, 270nm in height with its slab thickness of 50nm as shown in Fig. 2. The silicon waveguide is doped according to its defined region as shown in the figure. The doping dosage for both p+ and n+ regions per 1 μm are set to be $1 \times 10^{18} \text{ cm}^{-3}$ and p and n doping regions are doped at $5 \times 10^{17} \text{ cm}^{-3}$ and $2.5 \times 10^{17} \text{ cm}^{-3}$ respectively. A separate layer of surface oxide SiO_2 with thickness of 1 μm , is then placed on top and encompassing the silicon waveguide, with aluminum electrical contacts are attached to the waveguide's rib in order for free carrier diffusion electro-optic effect to take place. The initial simulation of the silicon waveguide block shows the propagation loss of the waveguide in quasi-TE transmission is 3.01dB/cm.

We have done the resonance response analysis of the micro-ring resonators in our previous works [19] and by selecting the optical wavelength operation of 1547.96nm, we can achieve the mode operation of the said micro-ring resonator as digital logic AND gate by applying a signal of 0.6V in amplitude to each of the input with its setup as shown in Fig. 3.

The ring outputs can be obtained from the through port as well as the drop port, but for this purpose, we select the output from the through port with its resonance response as shown in Fig. 4. The extinction ratio found from the design is 19.238dB.

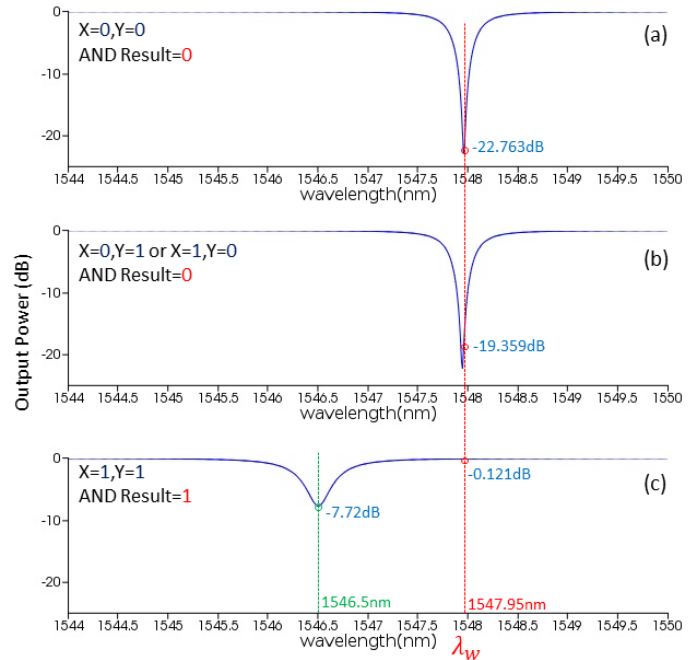


Fig. 4. Resonance spectra of the through port at specific logical inputs.

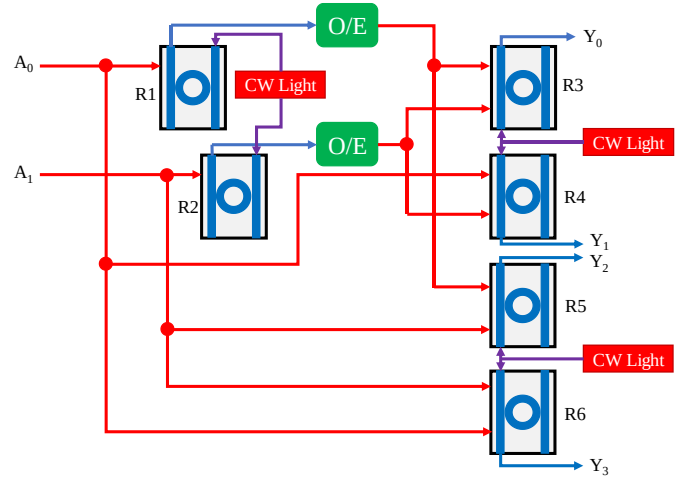


Fig. 5. Schematic setup for the 2 to 4 digital line decoder.

Once we are able to design the digital logic AND gates as well as the inverter based on silicon micro-ring resonator, we replace the logic blocks in Fig. 1 with micro-rings as well as other supporting components and the final design is as shown in Fig. 5. There are altogether six micro-ring resonators, four of which is operating as digital logic AND gates, while the remaining two operates as digital logic inverter. Each micro-ring takes electrical signals as its inputs and it outputs optical signals, thus photodetectors are required so that the output from one ring can be fed into other ring as its new input.

Digital line decoder operates by changing one of its logical outputs '1' (electrical voltage of 0.6V), while keeping the others logic '0' (electrical voltage of 0V). This is determined by what is injected as its input. At any time, only one output is at logic

state '1', and Each input combination is assigned to each output of the design.

When the input code is $(00)_2$, only output D0 is at logic state '1', while other outputs are at logic state '0'. Similarly, when the input is now $(01)_2$, only D1 is at logic state '1', with the remaining output at logic state '0'. When the input is now $(10)_2$, D2 is the only output to be at logic state '1' and when both inputs are at logic state '1', D3 outputs logic '1' while the others outputs the logic state '0'. The entire line decoder operation can be summarized in the Table 1.

TABLE I. 2 TO 4 LINE DECODER TRUTH TABLE

Inputs		Outputs			
A1	A0	D3	D2	D1	D0
0	0	0	0	0	1
0	1	0	0	1	0
1	0	0	1	0	0
1	1	1	0	0	0

TABLE II. MICRO-RING RESONATOR PROPERTIES

Parameters	Values
Operating Wavelength	1547.96nm
Ring Length	60 μ m
Coupling Gap	200nm
Waveguide Loss	3.01dB/cm
Effective Index Coefficient	2.56
Group Index Coefficient	4.41
Waveguide Mode	TE

III. SIMULATION AND ANALYSIS

The proposed design is simulated in one of the commercially available photonic integrated circuit simulation software known as Lumerical INTERCONNECT Solution. The entire setup for the time varying simulation is as shown in Fig. 6. A continuous wave (CW) laser source is used that generates a single optical wavelength of 1547.96nm with the optical power of 5dBm. The digital bit generator shown in Fig. 6 contains two elements, a Pseudo Random Bit Sequence (PRBS) generator coupled with the non-return zero (NRZ) pulse generator, connected to each of the input ports. The PRBS generator is configured to output sets of digital information of a repeating $(0011)_2$ and $(0101)_2$ for the inputs A1 and A0 respectively. The information selected is in accordance with the truth table shown in Table 1, thus enabling us to see if the proposed design is operating as desired. The NRZ pulse generator converts the bit sequences generated by the PRBS generator into electrical signals of amplitudes of 0.6V, with rise and fall time of 0.05ns.

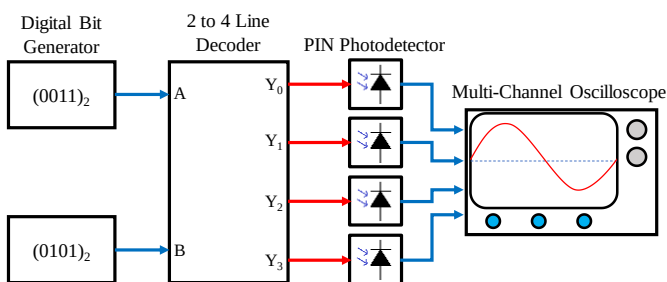


Fig. 6. Circuit setup for the time-varying simulation.

The optical to electrical converter used in this simulation as shown in Fig. 5 contains the avalanche photodiode (APD) photodetector connected in series with the Bessel low pass filter. The avalanche photodiode (APD) photodetector is used instead of PIN photodetector is due to APD exhibits the signal multiplication factor, which helps to amplify the electrical output signal which then feed into the low pass filter. The filter helps to filter out the unwanted high frequencies mostly generated by the photodetector, where the output is then sent as the input for the subsequent micro-ring resonator.

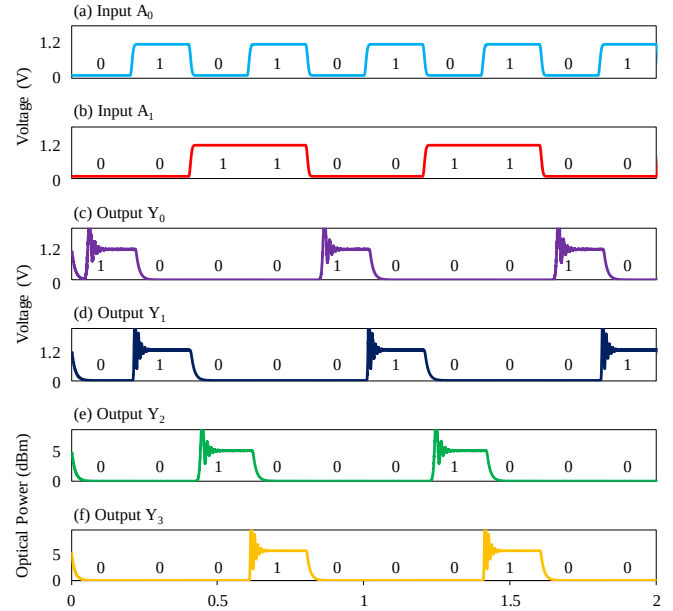


Fig. 7. Timing diagram for the proposed design of digital decoder.

Fig. 7 shows the results of the time varying simulations with the data rate of 5Gbps at the time window of 2ns. As can be seen from the figure, the generated outputs Y0, Y1, Y2 and Y3 in this case, it the same as the outputs D0, D1, D2 and D3 respectively from Table 1. All of the signals exhibit the overshoot and ringdown behavior when it is changing its logic state from '0' to '1', most probably due to the ring resonance is stabilizing its output due to the change in operation state. This effect can be reduced by applying low pass filters such as Bessel low pass filters. The rise and fall time for the output is found to be 0.082ns and fall time of 0.095ns respectively.

IV. CONCLUSION

This paper has presented the work of the design and simulation of a 2 to 4 digital electro-optic line decoder by using silicon micro-ring resonators as its core component. We have shown that the shift in resonance properties of a silicon micro-ring resonators can be used to design digital logic gates, with AND mode operation requires an electrical voltage of amplitude 0.6V in each of the input, and outputs an optical signal at the through port of the ring. A total of six silicon micro-ring resonators are used in our design, where these replaces the logic elements in each of the line decoder circuits. We have carried out time varying simulations with predetermined data bit stream, at the data rate of 5Gbps at the time window of 2ns to

demonstrate our proposed design operating as a 2 to 4 digital line decoder. Timing waveform suggests the clear optical signal at all four outputs, D0, D1, D2 and D3, presenting our proposed circuit design is capable of operating as a 2 to 4 digital line decoder.

ACKNOWLEDGMENT

We would like to thank Universiti Teknologi Brunei (UTB) for financial support to carry on this research.

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