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Micro-Ring Resonator-Based All-Optical Logic Gates and Combinational Logic Circuits

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Abstract— one of the most difficult foundations for photonic integrated circuits is silicon photonics (PIC). After the enormous success of Silicon photonics, the Micro ring resonator is crucial to it. All-optical logic gates are a crucial component in the design of many all-optical systems for optical signal processing. Optical computing is one of the most well-liked study disciplines because of its high bit rate. Electro-optic conversion makes optical signal processing with digital gates even more challenging. As a result, all-optical system design is required. In this article, All-Optical Logic gates and Combinational Logic circuits are designed using a 2 x 2 Silicon Micro Ring Resonator Switch. The suggested concepts include ultrafast all-optical silicon circuits.

Keywords: ***Optical gates; Optical computing; Micro ring Resonator; Optical Logic circuits; Silicon switches***

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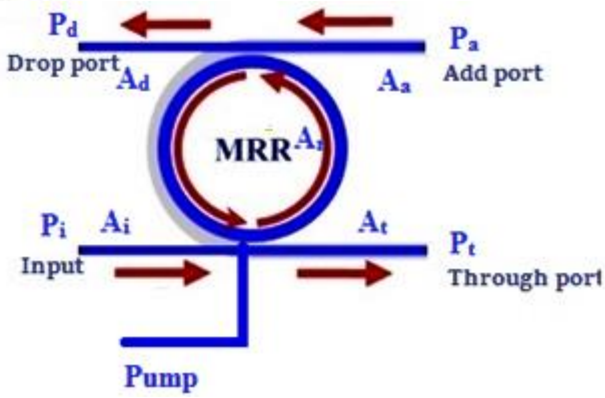
I. INTRODUCTION

ULTRA-fast and ultra-high bandwidth communication and computing are made possible by silicon-based Micro ring resonators. Silicon photonics uses a number of optical advantages to get over some of the problems that electronics has, like parallelism, high speed, and ultra-high bandwidth. Large-scale manufacture, ultrafast switching, and low power consumption are only a few advantages of silicon MRRs. The Micro-ring resonator functions as a 2x2 controlled optical switch that can serve as the central component of any circuit. The gates and logic circuits in all of these proposed designs use the fewest MRR switches possible. The experimental results provided by Xu and Li have been taken into consideration while computing the optical switching characteristics using 12 silicon MRR. The Micro ring modulators are the best PIC candidates due to their easy production, compact size, low cost, great sensitivity, and comparatively low voltage [1–7]. Due to a slight change in the intracavity's refractive index, the Classical Micro-Ring Modulator's operation focuses on the swing of resonant frequency [8]. The intracavity refractive index affects how sensitive the high-quality factor (Q) Micro ring is [9–12]. Handling photon lifetime limitation has been proposed in recent years by coupling intensity modulations [13–16].

A unlimited bandwidth has been demonstrated for coupling intensity modulators, such as Mach-Zehnder interference-based Micro-ring resonators (MZIMR) [17–19]. The phase-ring-enhanced MZIMR is another approach to raising the modulation frequency by including a phase ring in the MZI neighboring arm [20]. The Micro-ring Ring (MRR) is an optical device made of two linear waveguides connected to a circular cavity (Fig. 1). Laterally coupled MRR (LCMRR) and vertically coupled MRR (VCMRR) are the two methods used to build MRR [21]. A cross-coupling cannot occur between two straight waveguides that are vertical to one another in VCMRR. Even though both varieties of MRR have the same switching mechanism, in LCMRR two straight waveguides are parallel to one another and are ring coupled.



Ports A, B, A’ and B’ are input port, DROP port, ADD port, and THROUGH port. The electric fields of each port are, respectively, EA, EB, EA', and EB' [22]. Depending on the control pump pulse, a single MRR can function as a switch. Transmission occurs from A to A' and B to B' when the pump pulse S is off (S = 0), however when S is ON (S =

1), the circuit behaves like a 2x2 Swap circuit, with transmission occurring from A to B' and B to A', respectively. In order to enable coupling between them, the MRR combines straight waveguides in a region of one or more ring waveguides as a resonator cavity [23].

II. ALL-OPTICAL LOGIC GATES USING MICRO-RING RESONATOR

In all of these suggested designs, the all-optical logic gates have a maximum of two MRR switches. By setting up the MRR switch, each straightforward optical gate can be integrated in a different way [24].

2.1 All-Optical OR Gate

Similar to a basic OR gate, an all-optical OR gate uses optical laser signals instead of electrical ones. A single MRR switch is used to build an OR gate. In (Fig. 2(b)), the continuous light source is connected to the ADD port, which has two optical inputs, X and Y, where X corresponds to the INPUT port and Y to the CONTROL pulse. The DROP port is not connected, and THROUGH port is used as an output instead. Input X is sent to the THROUGH port (O/P) when CONTROL input Y is low, and when CONTROL input Y is high, the continuous light source is connected by Micro-ring to the THROUGH port. The OR gate will function as intended when both inputs are low, which prevents the light signal from being present at the O/P port.

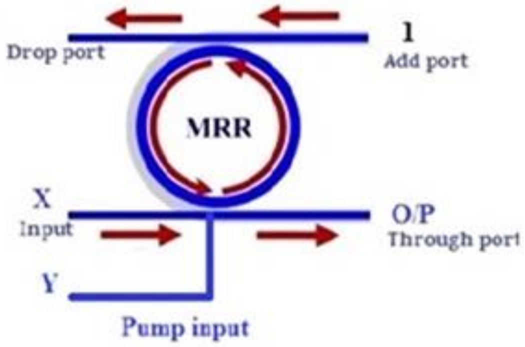


Fig. 2.1. All-Optical OR Gate

2.2 All-Optical AND Gate

Similar to a basic AND gate, but using optical laser impulses, is an all-optical AND gate. Design of an AND gate using a single MRR switch, two optical inputs (X and Y), a CONTROL pulse, and an additional input port (ADD port) connected to optical NULL. The THROUGH port is left disconnected and the output is obtained from the DROP port. When the CONTROL input Y is high, input X is transferred straight to the THROUGH port; when the CONTROL input Y is low, input X is connected to the DROP port (O/P) via Micro-ring. The DROP port receives the signal from the ADD port. Given the high values of both inputs and the presence of the light signal at the O/P port, the AND gate can function properly.

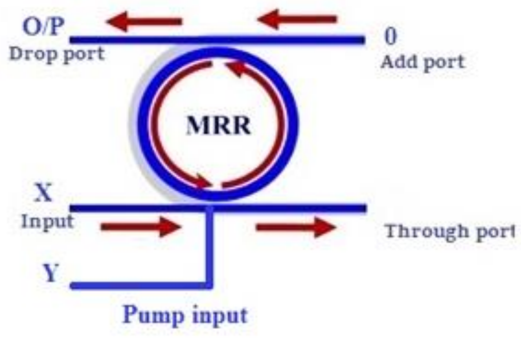


Fig. 2.2. All-Optical AND Gate

2.3 All-Optical NOT Gate

Similar to a normal NOT gate, an all-optical NOT gate operates on optical laser impulses. The NOT gate is designed using a single MRR switch as shown in Fig. 2(c), where input X has been given a CONTROL pulse, the INPUT port is connected to a continuous light source, and the second input port (ADD) is connected to an optical NULL. The DROP port is left unattached, while the THROUGH port is connected as an output. The continuous light source is linked to the DROP port (O/P) through Micro-ring, and CONTROL input X is high. When the input light source is directly connected to the THROUGH port and the CONTROL input X is low, the signal from the ADD port is sent to the DROP port. When control pulse X is low, the light signal is present at the O/P port; when control pulse X is high, the light signal is absent from the O/P port, providing the requirements for the NOT gate to function.

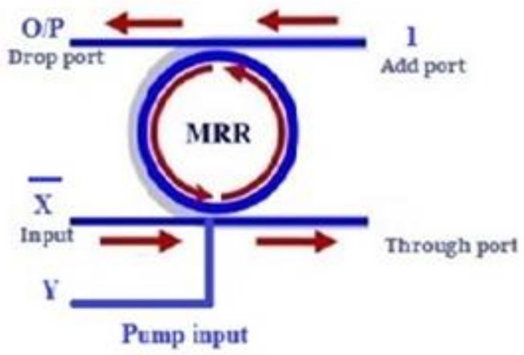


Fig. 2.3. All-Optical NOT Gate

2.4 ALL-Optical NOR Gate

Similar to a simple NOR gate, an all-optical NOR gate operates on optical laser impulses. NOR gate created using a single MRR switch and two optical inputs, X' and Y, as shown in Fig. 2(e). We require an inverter, or an additional MRR switch, to obtain X' as input. In this switch, X' is linked to the input port and Y is provided as the control pulse. A second input port, the ADD port, is connected to the optical NULL.

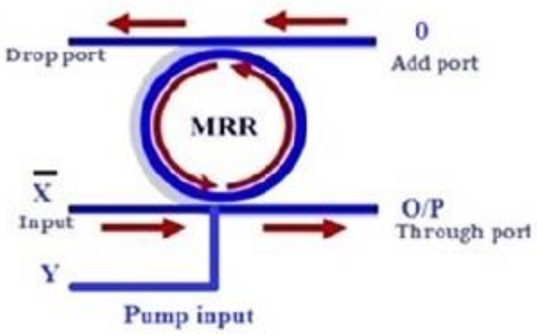


Fig. 2.4. All-Optical NOR Gate

2.5 All-Optical NAND Gate

Similar to a normal NAND gate, an all-optical NAND gate operates on optical laser impulses. NAND gate with two optical inputs, X'and Y, built by a single MRR switch as in (Fig. 2(d)); to obtain X'as input, we require an inverter, or another MRR switch. The INPUT port is given (X), and the CONTROL pulse is given (Y). Continuous light source is attached to another input port, the ADD port. The THROUGH port is left disconnected while the output is taken at the DROP port. When the CONTROL input Y is low, input X' is passed directly to the THROUGH port, and the ADD port signal is passed to the DROP port as no signal is given at the ADD port, which results in no signal being available at the output END. When the CONTROL input Y is high, input X' is connected to the DROP port(O/P) via Micro-ring. The light signal won't be present at the O/P port when both X and Y are high, enabling the NAND gate to function.

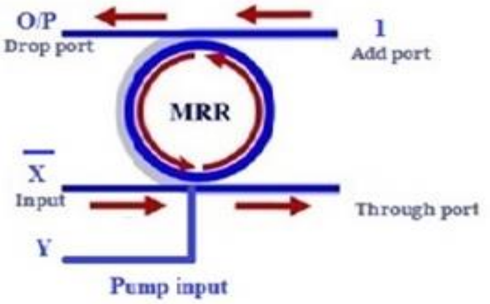


Fig. 2.5. All-Optical NAND Gate

III. ALL- OPTICAL COMBINATIONAL LOGIC CIRCUITS USING MICRORING RESONATOR

Logic gates are used to build logic circuits in traditional digital circuits. The same can be done in this case, however the MRR switch enables us to construct simple logic circuits directly using MRR switches. The MRR switch is used in the construction of the Half Adder/Half Subtractor, MUX/DEMUX [4] circuits.

3.1 All-optical Half Adder/ Half Subtractor

Similar to a standard Half Adder/Subtractor, an all-optical version uses optical laser signals as input and output instead of electrical signals. Two single-bit numbers are added or subtracted using the half adder/subtractor, and the results are displayed as sum/difference and carry/borrow. Two MRR switches are required to create a Half Adder/Subtractor circuit, with Y connected to the input port of MRR1 and Y'at the add port of MRR2. The design of a Half Adder/Subtractor utilizing MRR switches is depicted in (Fig. 3). X is provided to MRR1 and MRR2 as control inputs. Sum/Difference output is obtained from the MRR2's THROUGH port. Both Carry and Borrow outputs are received at the DROP and THROUGH ports of MRR1, respectively

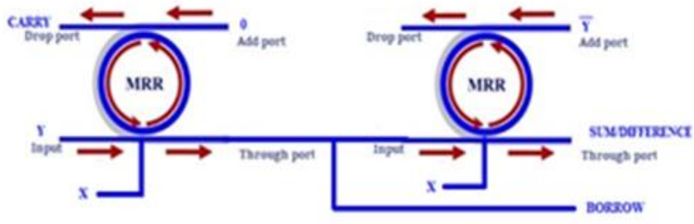


Fig. 3.1. Half Adder/ Subtractor

Case 1: All sum/difference, carry, and borrow outputs will be zero when X=0 and Y=0, both MRR switches will be OFF.

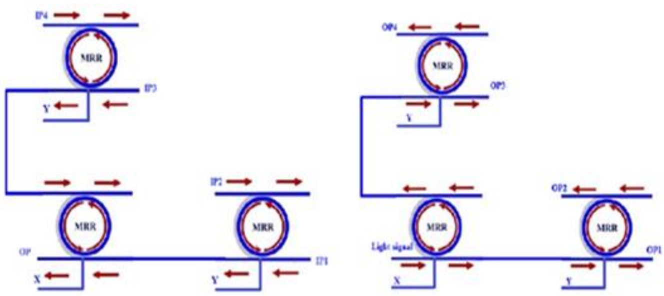
Case 2: The output carry will be 0 and the outputs sum/difference and borrow will both be 1 when X=0 and Y=1. Both MRR switches will also be OFF.

Case 3: When X=1 and Y=0, both MRR switches are turned on, the outputs carry and borrow are both set to 0, and the sum/difference is set to 1.

Case 4: Both MRR switches will be ON when X=1 and Y=1, the outputs will carry, sum/difference will be 1, and borrow will be 0.

3.2 MUX DEMUX

The most essential communication circuits are multiplexer and demultiplexer circuits. By sending many signals on the same channel, the multiplexer lowers the cost of the channel. The original signals are separated from the multiplexed signal using a demultiplexer. 1x4 DEMUX and 4x1 MUX both only need three MRR switches, similar to (Fig. 4).



(a) MUX (b) DEMUX

Fig. 3.2. MUX-DEMUX

MUX:

Assume that the four inputs are IP1, IP2, IP3, and IP4, and that X and Y are the two choose lines for the MUX circuit. Depending on the select line, inputs are connected to the output (OP).

Case 1: IP1 is linked to the output OP, X=0, Y=0, and all MRR are turned off.

Case 2: MRR1 is OFF, MRR2 & MRR3 are ON, X=0, Y=1. Through MRR2, IP2 is connected to the output OP.

Case 3: MRR1 is ON, MRR2 & MRR3 are OFF, X=1, Y=0.Through MRR3, IP3 is connected to the output OP.

Case 4: When X=Y=1 and MRR are all turned on, IP4 is connected to the output OP via MRR3 and MRR1.

DEMUX:

Assume a continuous wave (CW) light signal is input, and X and Y are the two select lines for the DEMUX circuit. OP1, OP2, OP3, and OP4 are connected with CW signal.

Example 1: X=Y=0

Every MRR is turned off, and the output is linked to OP1.

X=0, Y=1 in Case 2.

MRR1 is not active, while MRR2 and MRR3 are. Through MRR2, the output is linked to OP2

Case 3: X = 1, Y = 0. MRR1 is active, while MRR2 and MRR3 are not. Through MRR3, the output is linked to OP3

Example 4: X=Y=1 The output is linked to the OP4 through MRR3 and MRR1, and all the MRR are turned on.

IV. RESULTS AND DISCUSSION

All-optical gates have been developed for AND, OR, NOR and NAND. These all function similarly to basic gates but with input and output being optical laser impulses. Only when all of the inputs are high, the AND gate output is high; otherwise, it is low. Any of the inputs to the OR gate are high, and so is the output. NAND and NOR gates, respectively, combine the AND, OR, and NOT functions with the NOT function. They produce an output that is an addition to the output of AND and OR gates. When there are an odd number of high inputs, the XOR gate produces a high output. When either all of its inputs are high or all of its inputs are low, the XNOR gate produces a high output. The operating results of the circuits developed in accordance with their truth tables, as given in Table 1, are displayed in the line graphs created using the Optisystem programme below.

In the following graphs, the x-axis indicates the input values in the following ways: "1" denotes "X=0, Y=0," "2," "X=0, Y=1," "3," and "4" denotes "X=1, Y=1."

(Fig. 6(a)) displays the output of an AND gate as a high output at "4" only when the input is "X=1, Y=1".

A high output at positions 2, 3, and 4 that functions as an OR gate is shown in (Fig. 6(b)).

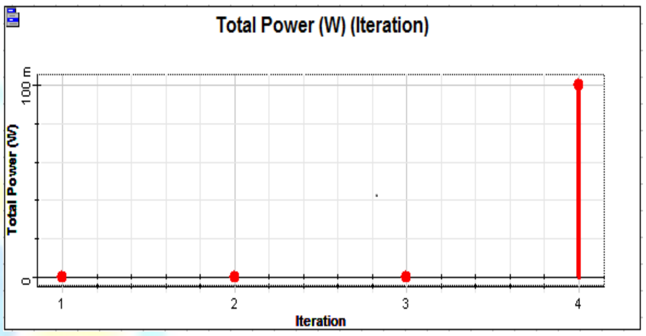
(Fig. 6(c)) inverts the inputs to produce an output that is high at "0" and low at "1" working as NOT gate.

(Fig. 6(d)) depicts a NOR gate with a high output that is only present at "0."

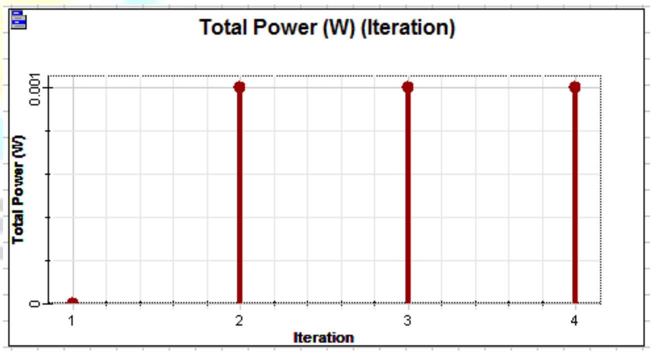
Working as a NAND gate, (Fig. 6(e)) only displays a low output at the values "4" or "X=1, Y=1".

Table 1. All Logic Gates Truth table

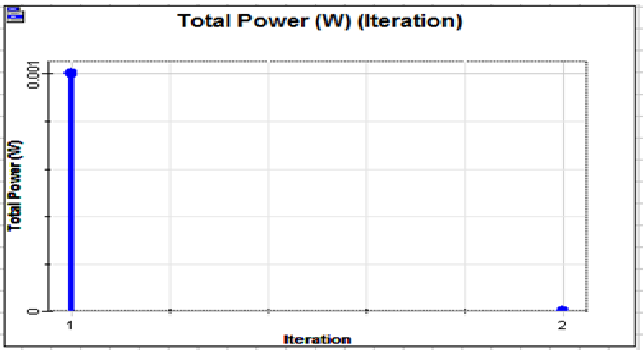
INPUTS		OUTPUTS			
X	Y	AND	OR	NAND	NOR
0	0	0	0	1	1
0	1	0	1	1	0
1	0	0	1	1	0
1	1	1	1	0	0



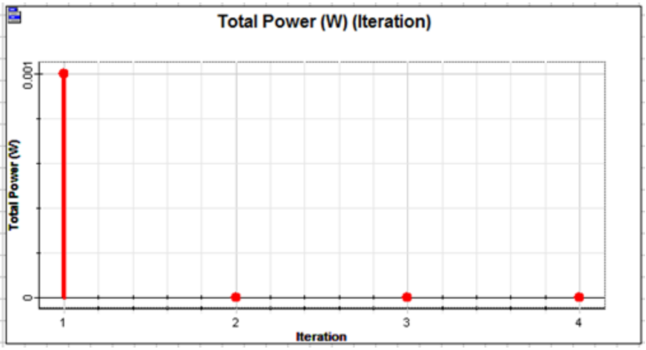
(a) AND Gate



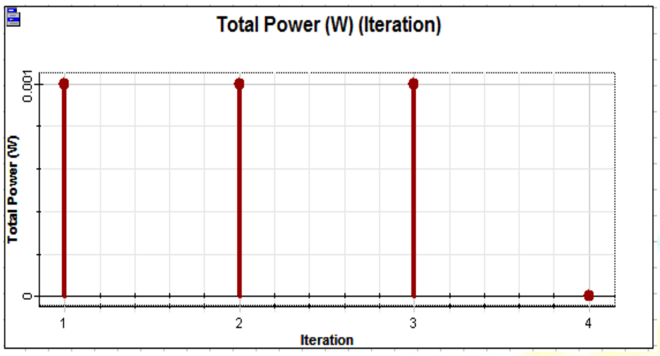
(b) OR Gate



(c) NOT Gate



(d) NOR Gate



(e) NAND Gate

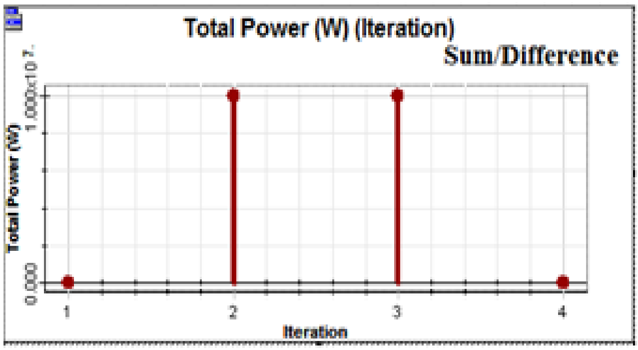
Fig. 4.All-Optical Gates Outputs (a) AND Gate (b) OR Gate (c) NOT Gate (d) NOR Gate (e) NAND Gate

Two separate binary digits are added or subtracted using the Half Adder/Subtractor circuit, which also outputs a carry or borrow value. As shown in the line graph below, it has been put into practise utilising optical laser signals as input and output.

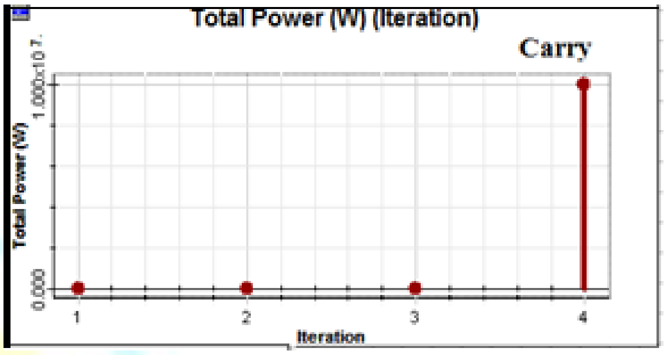
(Fig. 5(a)) contains the sum or difference when the inputs are "X=0, Y=1" and "X=1, Y=0," respectively, and the output values "2" and "3" are high. Only when the input is "X=1, Y=1" as shown in Figure 5(b) and "X=0, Y=1" as shown in Figure 5(c) is the value of carry and borrow high. Truth table for the half adder/subtractor as in Table 2.

(f) Table 2. Half Adder/Subtractor Truth table

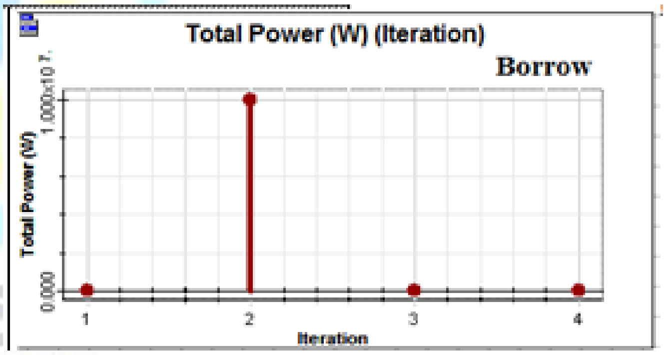
INPUTS		OUTPUTS		
X	Y	Sum/Difference	Carry	Borrow
0	0	0	0	0
0	1	1	0	1
1	0	1	0	0
1	1	0	1	0



(a) Half Adder Sum/ Half Subtractor Difference



(g) (b) Half Adder Carry



(h) (c) Half Subtractor Borrow

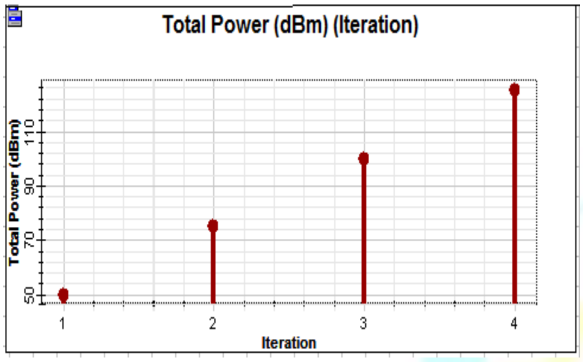
Fig. 5. Half Adder/ Subtractor (a) Half Adder Sum/ Half Subtractor Difference (b) Half Adder Carry (c) Half Subtractor Borrow

The MUX is a digital logic device that selects and forwards multiple optical inputs to a single optical output line and called as data selector. The line graph below illustrates how it has been put into practise. The numerous input values are represented by the fluctuating levels of each output line. The output is 50 W, just like in line 1, when the select lines are "X=-0, Y=0." As seen in line "2," the output is 75 W when the select lines are "X=0, Y=1." Line 3 of the result indicates that 100 W is produced when the select lines are "X=1, Y=0." 120 W is the output when the select lines are "X=1, Y=1," as shown in line 4. Figure 6 depicts the Multiplexer's output.

Table 3 has a MUX truth table.

(i) Table 3. MUX Truth table

Select Line Inputs		Outputs
X	Y	
0	0	IP1
0	1	IP2
1	0	IP3
1	1	IP4



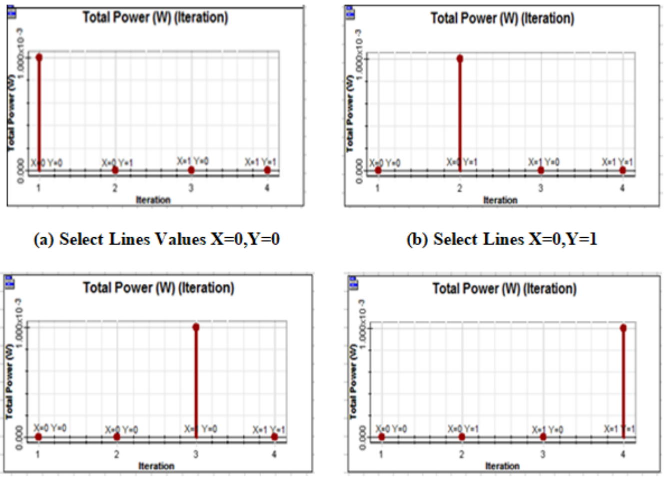
(j) Fig. 6. MUX Output

The DEMUX is digital logic device which has one input line, but its destinations to one of the many output lines. The line graph below illustrates how this was done utilising optical laser inputs and outputs. When the select line values are "X=0" and "X=0," the output line "1" is selected (Fig. 7(a)). The output line "2" is picked in (Fig. 7(b)) when the select line values are "X=0" and "X=1". When the select line values are "X=1" and "X=0," the output line "3" is selected (Fig. 7(c)). When the select line values are "X=1" and "X=1," the output line "4" is picked (Fig. 7(d)).

Table 4 contains a DEMUX truth table.

(k) Table 4. DEMUX Truth table

Select Line Inputs		Outputs
X	Y	
0	0	OP1
0	1	OP2
1	0	OP3
1	1	OP4



(a) Select Lines Values X=0,Y=0
(b) Select Lines X=0,Y=1
(c) Select Lines X=1,Y=0
(d) Select Lines X=1,Y=1

(l) Fig. 7. DEMUX Outputs (a) X=0,Y=0 (b) X=0,Y=1 (c) X=1,Y=0 (d) X=1,Y=1

V. CONCLUSIONS

The insight of ultrafast all the optical logic gates and combinational circuits with an optimum number of Micro-ring resonators has been proposed in this study. The Optisystem programme was used to create the line graphs displayed in Fig. 4 to 7, and the outputs are satisfactory for the operation of the gates and circuits. Thus created all-optical logic circuits can be employed in place of our current digital circuits. Thus, significant gains in speed and power efficiency are possible. Therefore, it will be essential for fiber optic communication, minimizing the drawbacks of the necessary electro-optic conversions.

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