Progress in Theoretical and Applied Physics
Vol. 1, 2013, 32-43
ISSN: 2320-3064 (Print), 2320-3072 (Online)
Published on 31 January 2013
www.researchmathsci.org

Progress in
Theoretical and Applied Physics

Design of Micro Ring Resonator Basedall Optical Adder/Subtractor

J.K.Rakshit[1], T.Chattopadhyay[2] and J.N.Roy[3*]

[1]Department of Electronics &Instrumentation Engineering,
National Institute of Technology Agartala, Tripura, India,
email: rakshitjk@rediffmail.com,
[2]Mechanical Operation (Stage-II), Kolaghat Thermal Power Station, WBPDCL,
West Bengal, India, email: tanayktpp@gmail.com,
[3]Department of Physics, National Institute of Technology Agartala, Tripura, India,
email: jnroys@yahoo.co.in

Received 29 September 2012; accepted 8 October 2012

Abstract. The need of high-speed digital optical computing systems and optical processors demands ultra-fast all-optical logic and arithmetic units. In this paper, we have exploited the attractive and powerful nonlinear property of the micro-ring resonator as an all optical switch to design an all-optical adder/subtractor (A/S) composite unit. We tried to exploit the advantages of ring resonator based optical switch to design an integrated all-optical circuit which can perform binary addition and subtraction. Computer simulation results confirming described methods are given in this paper.

Keywords: Optical micro-ring resonator, all optical switching, Adder–subtractor, all optical information processing.

1. Introduction

Parallel processing and ultra-high speed are two most important features required to enhance the over- all performance of any information processingsystem [1]. In computing, the processing speed is limited by the inherent property of the carriers.Rapidly growing ultra-high-speed and parallel processing optical communication and network needs to carry out switching, routing and processing in optical domain to avoid bottlenecks of optoelectronic conversions. In a pursuit to probe into cutting-edge research areas, all-optical technology is one of the most promising, and may eventually lead to new computing applications [2-5]as a consequence of faster processor speeds, as well as better connectivity and higher bandwidth. Research into this field has also explored new concept and ideas.

Recently much research has demonstrated the realization of various optical logic functions using different schemes like quantum dot SOA [6-7], Terahertz Optical Asymmetric Demultiplexer (TOAD) based interferometric devices [8-9] etc.

The advent of increasingly high speed, digital optical systems and optical processors demands an all-optical arithmetic unit to perform different optical arithmetic operations.The digital optical system and optical processor demands an all-optical adder/subtractor (A/S) composite unit to perform a set of optical arithmetic micro-operations.Various architectures, logical and/or arithmetic operations havebeen proposed in the field of optical/optoelectronic computing and parallel signal processing in the past few decades [10-13].

A lots of effort have been given for the development of fundamental all-optical logical functions (i.e.,adder/subtractor) by using different schemes like SOA-MZI based circuit [14-15], terahertz optical asymmetric demultiplexer (TOAD) based interferometric devices[9,16-17].Optoelectronic devices based on optical nonlinear micro-ring resonators [18-19] that strongly confine photons and electrons form a basis for next-generation compact-size, low-power and high-speed photonic circuits. Ring resonators have great potential advantages like incredibly small area consumption per ring, less complicity circuitry, narrow band, large free spectral range and high-wavelength selectivity. Ring resonators do not require gratings or faces for optical feedback and are thus suited for monolithic integration with other components. In addition, they are rather robust with respect to back reflections.

A micro-ring resonator based logic gates has already taken a significant role in the field of ultrafast all-optical information processing. Optical tree architecture (OTA) plays an important role in the optical interconnecting network. Here, we have tried to exploit the advantages of both OTA and the ring resonator based switch to design an all-optical circuit that can perform full adder and subtractor operations. In this paper, we report the GaAs-AlGaAsmicro-ring resonator based optimized device capable of carrying out the adder and subtractor operations simultaneously.

Operational principle of micro-ring resonator based optical switch is discussed in Section 2. Section 3 reports the theoretical design of micro-ring resonator based all optical adder and subtractor operations simultaneously. Simulation results confirming described method are also presented in Section 3. Paper ends with conclusion given in Section 4.

2. Micro-ring resonator based optical switch

The micro-ring-resonator (MRR) consists of unidirectional coupling between a ring resonator and input-output waveguides. A fraction k_1 (coupling co-efficient between input wave guide and the ring) of the incoming field is transferred to the ring having radius r as shown in Figure 1. When the optical path-length of a roundtrip is a multiple of effective wavelength, a constructive interference occurs and hence the MRR is “ON resonance”. As a consequence, periodic fringes appear at the output ports. At resonance, the drop port shows maximum transmission, since a fraction k_2(coupling co-efficient between the ring and output wave guide) of the built-up wave inside the ring is coupled to this port. In the through port the ring exhibits a minimum at resonance. If the resonator is made of a non-linear material, a logic switch can be produced. Through nonlinear effects, the refractive index can be changed by the intensity of light in the resonator. A green laser is used to pump the ring from top of the ring. Since the optical pump pulse is almost fully absorbed in the micro-ring waveguide the high density carriers are generated (pumping introduces extra electron-hole pair). These carriers effectively result in a net decrease of the refractive index of the micro-ring waveguide and cause a temporarily blue shift of the micro-ring resonance wavelength. This changing refractive index will cause the resonant wavelength to vary, which can then in turn be used to switch a signal on or off.

Now it is clear that in the absence of control signal (optical pump beam), the incoming signal at the input port of the ring reaches the drop port as shown in Figure 1. In this case no light is present in the through port. But in the presence of control signal (optical pump beam), the incoming signal at the input port reaches to the through port as shown in Figure 1. In this case no light is present at the drop port.
The field at the trough port (E_t) and drop port (E_d) can be expressed as

$$E_t = \frac{D\sqrt{1-k_1} - D\sqrt{1-k_2}\,x^2 \exp^2(j\phi)}{1-\sqrt{1-k_1}\sqrt{1-k_2}\,x^2 \exp^2(j\phi)} E_{i1} + \frac{-D\sqrt{k_1}\sqrt{k_2}\,x \exp(j\phi)}{1-\sqrt{1-k_1}\sqrt{1-k_2}\,x^2 \exp^2(j\varphi)} E_{i2} \tag{7}$$

$$E_d = \frac{-\sqrt{k_1}\sqrt{k_2}\,Dx \exp(j\phi)}{1-\sqrt{1-k_1}\sqrt{1-k_2}\,x^2 \exp^2(j\phi)} E_{i1} + \frac{D\sqrt{1-k_2} - D\sqrt{1-k_1}\,x^2 \exp^2(j\phi)}{1-\sqrt{1-k_1}\sqrt{1-k_2}\,x^2 \exp^2(j\phi)} E_{i2} \tag{8}$$

where,
$\varphi = \frac{k_n.L}{2}$, $x = D.\exp(-\alpha\frac{L}{4})$, $D = (1-\gamma)^{1/2}$, and L is the circumference of the ring($2\pi R$), the intensity attenuation coefficient of the ring is α, the intensity insertion loss coefficient of the directional coupler is γ and the wave propagation constant is k_n.

The above equations help to design a ring resonator as a switch and can also be used as a basic build block of adder/subtractor circuit which is described in Section 3.

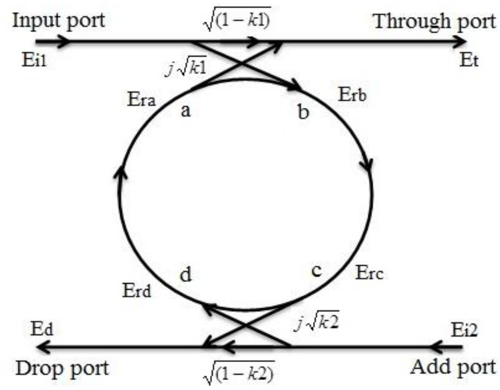

Figure 1. Single ring resonator

Simulated wave form for micro-ring resonator based optical switch is shown in Figure 2. A series of input signal [0011] and a series of control signal (pump beam) [0101] in the binary form is shown in Figure 2. From the simulation result, it is clear that if no signal is applied to the input then both output ports show zero result irrespective of control signal.When pump beam is not applied to the ring, the optical signal which is applied to the input of ring resonator comes to the drop port and when optical pump power is applied to the ring, the optical input signal which is applied to the input of the ring comes to the through port of the ring. All the simulated outputs of Figure 2 are summarized in the form of logical 0s and 1s in Table 2. In simulation, the parameters used are summarized in Table 1.

Table 1: Parameters and their optimum values used in simulation

Sl. No.	Parameter(s)	Value
1.	K_1=k_2(coupling coefficient for MRR)	0.25
2.	λ (resonant wavelength)	1.55 µm
3.	Radius of the ring	7.08 µm
4.	Effective cross sectional area	0.25 μm^2
5.	λ (resonant wavelength) with pumping power	1.5485 µm
6.	Change of refractive index when pumping power	3 X 10^{-3}

	applied	
7.	Intensity attenuation co-efficient of the ring	0.0005 μm^{-1}
8.	Insertion loss	5%

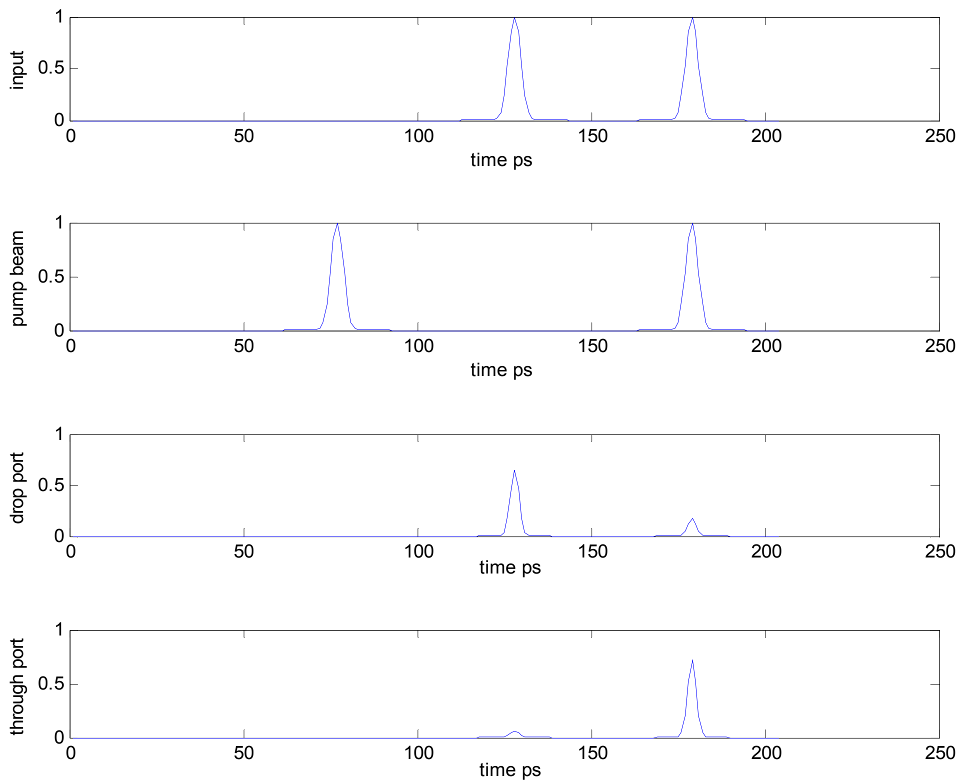

Figure 2. Simulation waveform of micro-ring resonator based optical switch

Table 2: Truth table of Figure 2

Incoming input signal	Control pump beam	Drop port output	Through port output
0	0	0	0

0	1	0	0
1	0	1	0
1	1	1	0

3. **All-optical full-adder and full-subtractor circuit**
A full adder circuit adds three single bit binary numbers (A,B,C_{in}) and gives result in two single bit binary outputs, called sum(S) and carry (C_{out}). The design of full adder circuit using micro-ring resonator based optical switch is shown in Figure 3.

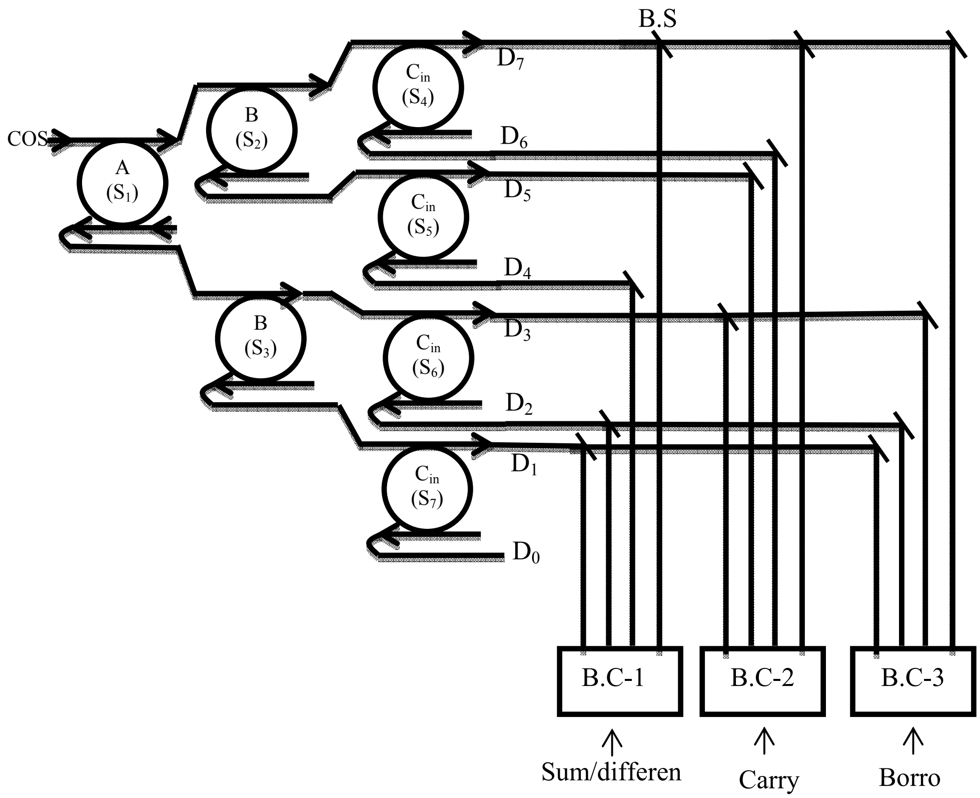

Figure 3: All optical full adder/subtractor circuit; B.C: Beam Combiner; \: Beam Splitter.

Depending upon the state of the variables (A,B,C_{in}) the output is obtained from one of the eight output terminals (D0 to D7). The all eight possible cases are describes in detail below.

Case-1: A=0, B=0, C_{in}=0;
First the light from the constant optical source (COS) is incident to the input of the first switch S_1. As the control signal A is off, the light emerges from the drop port and act as an input of switch S_3. As control signal B is also absent, the light follows the same principle and emerges from the drop of that switch which falls to the input of S_7 switch. Finally the light beam come the output D_0 through the drop port of S_7 as the control signal C_{in} is absent. So in this case, the output terminal D_0 is in high level (one state) and other output terminals are in low level(zero state) which gives the result of logical $\overline{A}.\overline{B}.\overline{C}_{in}$ operation.

Case-2: A=0, B=0, C_{in}=1;
Similarly, when first and second control signals (A,B) are off state and third control signal (C_{in}) is on state, the input signal comes to the through port of switch $S_7(D_1)$ which gives the result of logical $\overline{A}.\overline{B}.C_{in}$ operation.

Case-3: A=0, B=1, C_{in}=0;
Similarly, when first and third control signals (A,C_{in}) are off state and second control signal(B) is on state, the input signal comes to the drop port of switch $S_6(D_2)$ which gives the result of logical $\overline{A}.B.\overline{C}_{in}$ operation.

Case-4: A=0, B=1, C_{in}=1;
Similarly, when first control signal(A) is off state and second & third control signals (B,C_{in}) are on state, the input signal comes to the through port of switch $S_6(D_3)$ which gives the result of logical $\overline{A}.B.C_{in}$ operation.

Case-5: A=1, B=0, C_{in}=0;
When first control signal (A) is on state and second and third control signals (B,C_{in}) are off state, the input signal comes to the drop port of switch $S_5(D_4)$ which gives the result of logical $A.\overline{B}.\overline{C}_{in}$ operation.

Case-6: A=1, B=0, C_{in}=1;
When first and third control signals (A,C_{in}) are on state and second control signal (B) is off state, the input signal comes to the through port of switch $S_5(D_5)$ which gives the result of logical $A.\overline{B}.C_{in}$ operation.

Case-7: A=1, B=1, C_{in}=0;
When first & second control signals (A, B) are on state and third control signal (C_{in}) is off state, the input signal comes to the drop port of switch $S_4(D_6)$ which gives the result of logical $A.B.\overline{C}_{in}$ operation.

Case-7: A=1, B=1, C_{in}=1;

When all the control signals (A, B, C_{in}) are on state, the input signal comes to the through port of switch $S_4(D_7)$ which gives the result of logical $A.B.C_{in}$ operation. The above all eight conditions are listed in Table 3.

Table-3: State of different output terminals for different input variables

Inputs			Outputs of different terminals							
A	B	C_{in}	D_0	D_1	D_2	D_3	D_4	D_5	D_6	D_7
0	0	0	1	0	0	0	0	0	0	0
0	0	1	0	1	0	0	0	0	0	0
0	1	0	0	0	1	0	0	0	0	0
0	1	1	0	0	0	1	0	0	0	0
1	0	0	0	0	0	0	1	0	0	0
1	0	1	0	0	0	0	0	1	0	0
1	1	0	0	0	0	0	0	0	1	0
1	1	1	0	0	0	0	0	0	0	1

In case of full adder we have two outputs one is sum (S) and another is carry (C_{in}). The sum take the expression as S= $\overline{A}.\overline{B}.C_{in} + \overline{A}.B.\overline{C}_{in} + A.\overline{B}.\overline{C}_{in} + A.B.C_{in}$ and carry takes the expression as C_{out}= $\overline{A}.B.C_{in} + A.\overline{B}.C_{in} + A.B.\overline{C}_{in} + A.B.C_{in}$. So the sum (S) is taken from combining D_1, D_2, D_4, D_7 with a beam combiner (B.C-1) and the carry (C_{out}) is taken from combining D_3, D_5, D_6, D_7 with a beam combiner (B.C-2). The corresponding simulation result is shown in Figure 4. The corresponding truth table of full adder for three input binary variables is shown in Table 4.

Table 4: Truth table of full adder.

Inputs			Output	
A	B	C_{in}	Sum	Carry
0	0	0	0	0

0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

A full subtractor circuit can be implemented using the same circuit (Figure 3). A combinational circuit of full subtractor performs the operation of subtraction of three binary bits-minuend (A), subtrahend (B) and borrow (C_{in}) generated from subtraction operation of previous significant digits and produces the outputs called difference (D) and borrow (B). Here, difference can be expressed as D= $\overline{A}.\overline{B}.C_{in} + \overline{A}.B.\overline{C}_{in} + A.\overline{B}.\overline{C}_{in} + A.B.C_{in}$ and borrow can be expressed as B= $\overline{A}.\overline{B}.C_{in} + \overline{A}.B.\overline{C}_{in} + \overline{A}.B.C_{in} + A.B.C_{in}$. Now, if we combine the result of output terminals of D_1, D_2, D_4, D_7 we obtain the result of difference, whereas combination of results of output terminals D_1, D_2, D_3, D_7 gives the result of borrow.

The corresponding simulation result is shown in Figure 4. The corresponding truth table of full subtractor for three input binary variables is shown in Table 5.

Table 5: Truth table of full subtractor.

Inputs			Output	
A	B	C_{in}	difference	Borrow
0	0	0	0	0
0	0	1	1	1
0	1	0	1	1
0	1	1	0	1
1	0	0	1	0
1	0	1	0	0

1	1	0	0	0
1	1	1	1	1

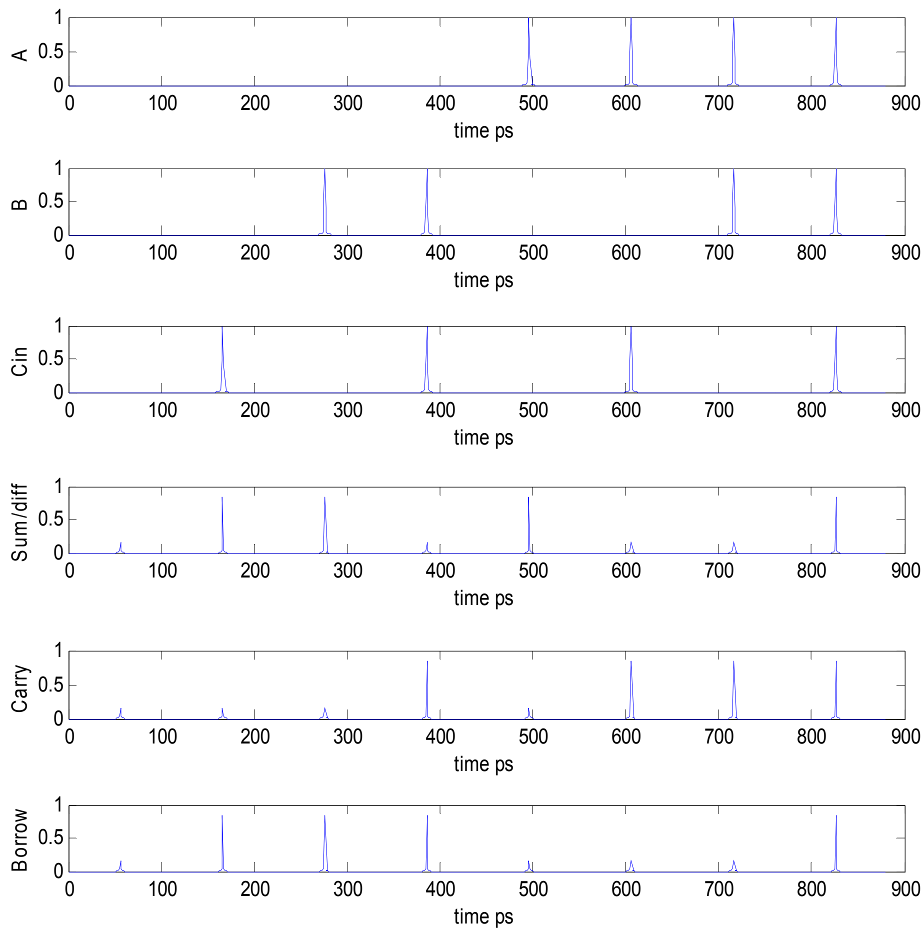

Figure 4: Simulation results of full adder/subtractor.

4. Conclusion

The detailed theoretical analysis of all optical switching in GaAs-AlGaAs micro-ring resonator using optical pumping method has been explained. We have proposed ultra-fast adder/ subtracter circuits where the input signals and the control signals are all-optical in nature. The same architecture can be used for different purposes. This scheme can easily and successfully be extended and implemented for any higher number of input digits by proper incorporation of ring resonator-based optical switches.Computer simulation results confirming described methods are given in this paper.

REFERENCES

1. G. P. Agrawal, Lightwave Technology: Components and Devices (Wiley, 2004).
2. W.M.J.Green, R.K.Lee, G.A.DeRose, A.Scherer, and A.Yariv, Hybrid InGaAsP-InP Mach-Zehnder Racetrack Resonator for Thermooptic Switching and Coupling Control, Optics Express, 13(5), 1651 (2005).
3. H.J.Caulfield and S.Dolev, Why future supercomputing requires optics, Nature Photonics, 4, 261 – 263 (2010).
4. D.Woods and T.J.Naughton , Optical computing: Photonic neural networks, Nature Physics,8, 257–259 (2012).
5. D. Woods and T. J. Naughton, Optical computing applied mathematics and computation, 215(4), 1417-1430, (2009) (Special issue on Physics and Computation).
6. S.Ma, Z.Chen, H.Sun and K.Dutta, High speed all optical logic gates based on quantum dot semiconductor optical amplifiers, Opt. Express, 18 (7) 6417–6422 (2010).
7. E.Dimitriadou and K.E.Zoiros, On the design of ultrafast all-optical NOT gate quantum-dot Semiconductor optical amplifier based Mach-Zehnder interferometer, Optics and Laser Technology,44, 600-607 (2012).
8. D.K.Gayen and J.N.Roy, All-optical arithmetic unit with the help of terahertz-optical-asymmetric-demultiplexer-based tree architecture, Applied Optics, 47, 933-943 (2008).
9. J.N.Roy, and D.K.Gayen, Integrated all-optical logic and arithmetic operation with the help of a TOAD-based interferometer device-alternative approach, Appl. Opt., 46, 5304-5310 (2007).
10. D.K.Gayen, A.Bhattacharyya and J. N. Roy, Ultrafast all optical Half Adder using Quantum-Dot semiconductor Optical Amplifier-based Mach-zehnder Interferometer, Journal of Light wave Technology, 2012[in press].
11. A. J. Poustie, K. J. Blow, A. E. Kelly and R. J. Manning, All optical full-adder with bit differential delay, Opt. Commun. 156, 22–26 (1998).
12. I. Glesk, R. J. Runser, and P. R. Prucnal, New generation of devices for all-optical communication, Acta Phys. Slov. 51, 151–162 (2001).
13. J. N. Roy, A. K. Maiti and S. Mukhopadhyay, Designing of an all-optical time division multiplexing scheme with the help of nonlinear material based tree-net architecture, Chin. Opt. Lett. 4, 483–486 (2006).
14. J.N.Roy, Mach–Zehnder interferometer-based tree architecture for all-optical logic and arithmetic operations, Optik 120, 318–324(2009).
15. A.K.Cherri and A.S.Al-Zayed, Circuit designs of ultra-fast all-optical modified signed-digit adders using semiconductor optical amplifier and Mach–Zehnder interferometer, Optik 121, 1577–1585(2010).

16. D.K.Gayen, R.K.Pal and J.N.Roy, All-optical adder/subtractor based on terahertz optical asymmetric demultiplexer, Chinese Optics Letters, 7(6),530-533(2009).
17. D.K.Gayen, C.Taraphdar, J.N.Roy and R.K.Pal, Terahertz optical asymmetric demultiplexer based all optical data comparator, Journal of Circuits Systems and Computers, 19(3) 671-682 (2010).
18. S.Lin, Y.Ishikawa, and K.Wada, Demonstration of optical computing logics based on binary decision diagram, Optics Express, 20(2), 1378-1384 (2012).
19. T.A.Ibrahim, K.Ritter, P.P.Absil, F.G.Johnson, R.Grover, J.Goldhar, P.T.Ho, All optical nonlinear switching in GaAs-AlGaAsmicroring resonators, IEEE Photonics Technology Letters, 14(1),74-76 (2002).