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A NOVEL METHOD OF IMPLEMENTING NONLINEAR MATERIAL BASED ALL-OPTICAL BINARY HALF SUBTRACTOR AND FULL SUBTRACTOR SYSTEM

Samir **Sahu**[(a)*], Radha **Raman Pal** [(b)] , Shantanu **Dhar** [(c)]
[(a), (b)]Department of Physics and Technophysics, Vidyasagar University, Midnapore – 721102, West Bengal, India
[(c)]Department of Physics, Jhargram Raj College, Jhargram – 721507, West Bengal, India
*Corresponding auther. E-mail: tosamirsahu@gmail.com

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Abstract

In this paper we describe novel all-optical binary subtractors that demonstrate the ability of all-optical digital processing to perform subtraction operations with logic circuits in direct manner. All-optical switching mechanism is exploiting here to realize the all-optical binary subtractors. The all-optical switch by a composite slab of linear medium and non-linear medium is the building block of our proposed subtraction circuits. An all-optical half-subtractor which is followed by a full-subtractor has been developed. These circuits are simple and all-optical in nature. It can also gear up to the highest capability of optical performance in high-speed all-optical computing system.
Key words: Nonlinear material, All-optical switch, Half-subtractor, Full-subtractor.

I. INTRODUCTION

With the increment of data traffic day-by-day, there is a requirement to restrict research problems in a particular region to achieve the reliable, faithful and high speed performances in computation [1-3, 5] and communication [4, 6]. In this regard, the limitations [1-3, 5, 7, 9] of electronics are familiar. Signal processing in all-optical domain is essential in future high bit-rate communication and computation to avoid electronics bottleneck. We have to replace electronics with photonics [1-7, 9]. All-optical techniques for processing light wave-computation signals have advanced significantly in last few years. Indeed, intensive research has produced practical all-optical devices for various arithmetic [1, 5, 9], logic [2-3, 13], algebraic [7] operations. As these types of optical systems require some optical switches, design of all-optical switches is of great interest to the photonics community. Non linear material (NLM) has established its validity as optical switching devices [1-3, 5, 9].

The all optical implementation of various subtraction schemes [5] have been studied by taking the complement of the subtrahend and adding it to the minuend. The schemes for optical implementation of subtractors using Semiconductor Optical Amplifier (SOA) [6] and electro-optic-modulators (EOM) [11] have been attempted. The paper presents a scheme for the implementation of all optical Half Subtractor and Full Subtractor with logic circuits in direct manner [8, 10], as done with paper and pencil, by nonlinear optical material based switching mechanism, in such a way that will obey the truth tables as shown in Table 2 and 3 [8, 10].

II. ALL-OPTICAL SWITCHING BEHAVIOR OF NONLINEAR MATERIAL

The phenomenon photorefractivity [13, 14] of some nonlinear optical material is used in nonlinear all-optical intensity switching mechanism. The photorefractive effect, where the refractive index changes induced by a light field when the crystal is subjected to intense laser radiation, defocusing and scattering of the light, is observed, as a result of an inhomogeneous change in the refractive index. It is also found that these changes still prevail even after the light is switched off, but it could be erased by strong, uniform illumination [14].The refractive index of some nonlinear materials (NLM) such as carbon disulfide, pure silica, potassium dihydrophosphate (KDP) crystal etc. varies linearly with the intensity of the light incident on it. The refractive index (n) of such isotropic dielectric non-crystalline media can be put into an equation as $n = n_0 + n_1 I$. Here n_0 is the linear term, n_1 is the nonlinear correction term and I is the intensity of the incident light beam on the material.

We can implement the switching mechanism with such nonlinear material by taking an interface between two media of which one is a linear material (LM), whose refractive index n_0 is independent of the intensity of light and the other is aforesaid NLM. A laser beam, highly intense polarized light, preferably pulse laser of intensity I_1, is allowed to incident on the interface from linear to nonlinear part in a particular direction XO (incidence angle θ_1) as depicted in Fig. 1. The refracted beam from the NLM follows the path OZ. But when another higher intense laser beam of intensity I_2 ($I_2 > I_1$) is made to incident along XO, after refraction from the NLM the light passes through OY direction (angle of refraction θ_2). The deviation of refractive angle for different incident light intensity I_1 and I_2 is $\angle ZOY = \Delta\theta_2$. Thus the combination of LM and NLM may act nicely as a directional all-optical switch. This is the unit block of our proposed subtraction circuit.

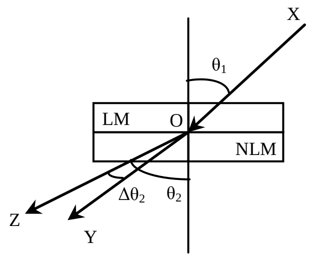

Fig. 1 : Intensity switching of optical nonlinear material

In the expression of refractive index $n = n_0 + n_1 I$, n_0 is linear term and n_1 is the nonlinear correction term. For carbon disulfide [2, 3, 12] (CS_2) $n_0 = 1.63$, $n_1 = 514\times10^{-20}$ m^2/W. and for fused silicon dioxide [2, 3, 12] (SiO_2) $n_0 = 1.458$, $n_1 = 2.7\times10^{-20}$ m^2/W. If we use CS_2 and SiO_2 as nonlinear materials and the pulse laser of intensity $I = 2\times10^{18}$ W/m^2 as a source, we can estimate the deviations of light in two cases as given in Table 1.

Table 1

Estimation of the deviation of pulsed laser light when passing through carbon disulfide(CS_2) and silicon dioxide(SiO_2).

Material	Angle of incidence (θ_1)	Incident light intensity	n ($= n_0 + n_1 I$)	Angle of refraction (θ_2)	Deviation ($\Delta\theta_2 = \theta'_2 - \theta''_2$)
carbon disulfide (CS_2)	45 deg	$I=2\times10^{18}$ W/m^2	11.91	3.404 deg = θ'_2	1.578 deg
	45 deg	2I	22.19	1.827 deg= θ''_2	
silicon di-oxide (SiO_2)	45 deg	$I=2\times10^{18}$ W/m^2	1.512	27.883 deg= θ'_2	1.041 deg
	45 deg	2I	1.566	27.842 deg= θ''_2	

The logic gates [1-3, 5, 13] are implemented in optics using NLM by taking the presence of light signal as 1 and the absence of it as 0. The implementation of such logic gates can be done by using some femtosecond laser pulses and 1-mm-thick potassium dihydrophosphate (KH_2PO_4 (KDP) crystal at the pick intensity of 0.6 TW/cm^2 and duration of 60 fs [3-4].

III. ALL-OPTICAL NOT GATE AND EX-OR GATE

III. 1 All Optical NOT gate

To implement an all optical NOT gate using non-linear material a constant intensity pulse laser source (CILS) is used as shown in Fig. 2. It is also called probe beam. Here P_1 is taken as input beam. A detector is placed at P_2 will detect the output beam after refraction. If P_1 is absent, the light will follow a path OP_2 and will be detected by the detector due to presence of CILS. But if P_1 is present, after refraction, the light will follow a path other than OP_2, may be OP_3, and the detector will not detect any light signal. Thus the system acts as optical NOT gate.

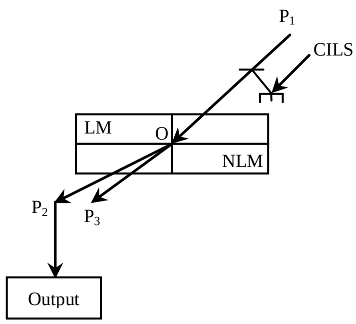

Fig. 2 : All-optical NOT

III. 2 All-optical Ex-OR gate:

The two inputs all-optical XOR gate using NLM is shown in Fig 3. Here D_1 and D_2 are two input channels. A detector placed at D_3 gives the output. When only one input channel carries light signal, the light beam after refraction will detect by the detector at D_3, unless not.

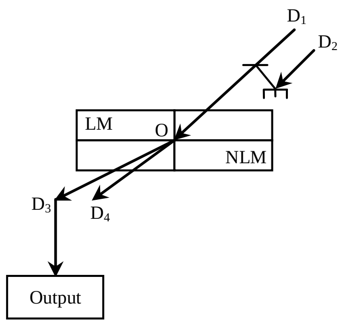

Fig. 3 : All-optical EX-OR gate

IV. ALL-OPTICAL BINARY SUBTRACTORS

IV. 1. Half Subtractor

Fig. 4 illustrates a process to perform 1 bit binary all-optical subtraction scheme. It is made of with the three combinational blocks of linear and nonlinear material. Here NG is an all-optical NOT gate and AG and EG are two input AND gate and EX-OR gate respectively. These three gates form an all-optical half subtractor. A_0 and B_0 are the two binary input beams. Designate the minuend bit by A_0 and the subtrahend bit by B_0. CILS, a probe beam, is used here to act NG block as NOT gate. Two detectors placed at C_0 and D_0 gives the outputs. Light at D_0 indicates the DIFFERENCE. Also the light at C_0 indicates the presence of BORROW bit of the result of the one bit subtraction.

First we want to subtract binary number 0 from another binary number 0. So $A_0 = 0$ and $B_0 = 0$. At P_1 from NG we get the complemented output of A_0 due to the presence of CILS (i.e. $P_1 = \overline{A_0}$). P_1 and B_0, the two inputs of AND gate (AG), now become 1 and 0 respectively. As a consequence the output C_0 (BORROW) will be 0. On the other hand, as both the inputs of the EX-OR gate (EG) are 0 the output D_0 gives 0 which is the DIFFERENCE bit. It means BORROW = 0 and DIFFERENCE = 0. The output result is 00. This represents 0 – 0 = 00.

Let us think about the subtraction of 1 from 0. Here $A_0 = 0$ and $B_0 = 1$. It means A_0 is less than B_0 and 1 is borrowed from the next higher stage and added 2 to the minuend. As A_0 = 0 the output of NG, P_1 = 1. Now both the input (P_1 and P_2) channels carry light for AG. One can expect light at C_0 terminal (i.e. BORROW = 1). The inputs (A_0 = 0 and B_0 = 1) of EX-OR gate (EG) are different. The output light signal will follow the path O_2P_3, no light will go through the line O_2P_4, which yields D_0 = 1. This indicates BORROW = 1 and DIFFERENCE = 1. Here we obtained the output result 11 of (0 - 1).

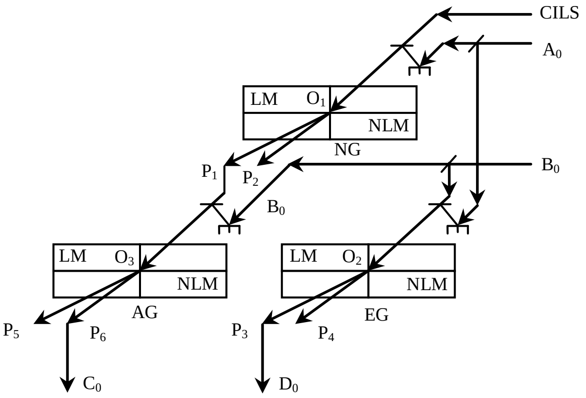

Fig. 4 : All-optical half-subtractor

Next, we like to subtract 0 from 1. That is A_0 = 1 and B_0 = 0. The input A_0 (=1) is inverted at the terminal P_1 (= 0) when light passing through the NOT gate. Now both the input beams of the AND gate (AG) have photon (P_1 = P = 0). So, the BORROW output is obviously equal to 0. Just like the previous case, the inputs (A_0 = 1 and B_0 = 0) of AG are different and the output light beam will travel along the path O_2P_3. This gives BORROW = 0 and DIFFERENCE = 1. The output result is 01 of (1 - 0).

Finally, let us take the case of subtraction from 1 to 1. Here A_0 = B_0 = 1. Due to the absence of light through O_1P_1 path, P_1 is equal to 0 (= $\overline{A_0}$). As any one of the input of a AND gate is 0 the output will be 0, whatever may be the other input. So, C_0, the BORROW bit equals to 0. Both the inputs of the EG are equal. There will be darkness at D_0 which means BORROW = 0 and DIFFERENCE = 0. The corresponding output result of the half subtractor is 00.

Table 2
Truth table of half subtractor

Inputs		Outputs	
A_0	B_0	C_0	D_0
0	0	0	0
0	1	1	1
1	0	0	1
1	1	0	0

IV. 2. Full Subtractor.

A design of all-optical full subtractor is shown in Fig. 5. Three combinational blocks of linear and nonlinear material are required to design it. Here NG is an all-optical NOT gate with a constant intensity pulse laser source (CILS). E_1, the output of NG is nothing but $\overline{A_n}$. QG and RG are the rest two three-input unit blocks. The detector is so placed that if any one input at a time or all inputs of QG are at logical 1 state then the output (D_n) of QG becomes 1, otherwise not. C_n, the output of the block RG carry light if any two at a time or all the input channels have photon. A_n, B_n and C_{n-1} are the three binary input beams designated as the minuend bit, the subtrahend bit and the BORROW from previous stage subtractor respectively. Two detectors placed at C_n and D_n gives the outputs. Light at D_n indicates the DIFFERENCE. Also the light at C_n indicates the present stage BORROW bit of the result of the bit by bit subtraction. As there is three inputs, A_n, B_n and C_{n-1} eight cases may arise.

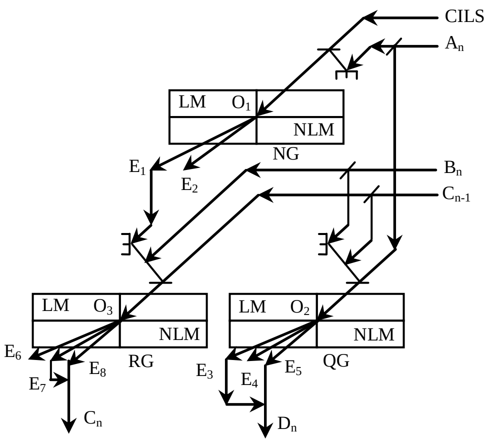

Fig. 5 : All-optical full-subtractor

In the first case, $A_n = B_n = C_{n-1} = 0$. So, E_1 becomes 1 by the NOT gate by the presence of probe beam. As only one input (E_1) of RG is 1 and the other two inputs ($B_n = C_{n-1} = 0$) are not 1, C_n (BORROW) remains dark. On the other hand for QG all inputs are at 0 states. Then one cannot get light at D_n (DIFFERENCE). This represents 0 – 0 – 0 = 00.

In the second case, $A_n = B_n = 0$ and $C_{n-1} = 1$. So, A_n becomes E_1 (= 1) when passing through NG. As two inputs (E_1 and C_{n-1}) are equal to 1 and $B_n = 0$, C_n must be 1 which is the BORROW bit. Again, for block QG only one input (C_{n-1}) carries light. So, the DIFFERENCE bit, D_n carries light. Here the output is 11 for (0 – 0 – 1).

Next, we take $A_n = 0$, $B_n = 1$ and $C_{n-1} = 0$. Then E_1 turns out to be 1. Like the previous case, BORROW bit, C_n gives 1 because only two inputs signals (E_1 and B_n) are at 1 state but not the third one ($C_n = 0$). On the contrary, $B_n = 1$ (only one input of QG) which yields D_n as 1. The final result is ones again 11 of (0 – 1 – 0).

Now, for $A_n = 0$ and $B_n = C_{n-1} = 1$ we have E_1 = 1. All the three inputs (E_1, B_n and C_{n-1}) are equal to 1 giving $C_n = 1$ which is the BORROW bit. The output D_n of the block QG remains dark, as only two inputs ($B_n = C_{n-1}$) are at 1. The corresponding result is $C_nD_n = 10$.

Here, $A_n = 1$ and $B_n = C_{n-1} = 0$. Then obviously $E_1 = 0$. All the three inputs (E_1, B_n and C_{n-1}) are equal to 0, giving the final BORROW output, $C_n = 0$. As there is light at only one input channel (A_n), one can obtain light at D_n. We get 1 – 0 – 0 = 01.

In this condition, we assume A_n and C_{n-1} are at logical high state but B_n remains at low state. Sequentially, $E_1 = 0$, as E_1 is the complement of A_n. The block RG is compelled to give $C_n = 0$ because only one input line (C_{n-1}) transmits light. D_n also is equal to 0, as two inputs A_n and $C_{n-1} = 1$. So, $C_nD_n = 00$.

Here in this possibility, we consider $A_n = B_n = 1$ and $C_{n-1} = 0$ which gives $E_1 = 0$. Now the RG block has only one input (B_n) as 1. So, the BORROW bit, C_n becomes 0. The other output (D_n) from QG also becomes 0 due to the presence of light at two input terminals A_n and B_n. The corresponding output is 00 (1 – 1 – 0).

Table 3
Truth table of full subtractor

Inputs			Outputs	
A_n	B_n	C_{n-1}	C_n	D_n
0	0	0	0	0
0	0	1	1	1
0	1	0	1	1
0	1	1	1	0
1	0	0	0	1
1	0	1	0	0
1	1	0	0	0
1	1	1	1	1

In the last option, all the three inputs A_n, B_n and C_{n-1} may be assumed active i.e. $A_n = B_n = C_{n-1} = 1$. So, E_1 will be inactive. In RG, the light traverses along O_3E_7 direction, to give $C_n = 1$, because only B_n and C_{n-1} terminals have light. Now for QG all the inputs A_n, B_n and C_{n-1} are at 1 state, that indicates D_n will be 1. We obtain the output of the full subtractor 11 of (1 – 1 – 1).

V. CONCLUSION

Our proposed circuits are very much reliable because they follow the basic principle of subtraction operation. The light signals that are severally used, bended light signals from the outputs are made by mirrors and beam splitters to make the circuits simple. As the circuit is purely all-optical in nature and very simple, one can obtain the speed of operation far more than THz limit. This subtraction scheme should be the first step on our dream way to all-optical Arithmetic Unit. The entire scheme should perform properly using suitable nonlinear material [2, 3, 12, 15]. Essentially inputs should be chosen properly for proper function of the system.

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