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

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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 \( \theta_1 \)) 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 \( \theta_2 \)). The deviation of refractive angle for different incident light intensity \( I_1 \) and \( I_2 \) is \( <ZOY = \Delta \theta_2 \). 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](image-url)

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] \( (CS_2) \) \( n_0 = 1.63, n_1 = 514 \times 10^{-20} \text{ m}^2/\text{W} \). and for fused silicon dioxide [2, 3, 12] \( (SiO}_2 \) \( n_0 = 1.458, n_1 = 2.7 \times 10^{-20} \text{ m}^2/\text{W} \). If we use \( CS_2 \) and \( SiO}_2 \) as nonlinear materials and the pulse laser of intensity \( I = 2 \times 10^{18} \text{ W/m}^2 \) as a source, we can estimate the deviations of light in two cases as given in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Angle of incidence (( \theta_1 ))</th>
<th>Incident light intensity</th>
<th>( n ) (= ( n_0 + n_1 I ))</th>
<th>Angle of refraction (( \theta_2 ))</th>
<th>Deviation (( \Delta \theta_2 = \theta_2' - \theta_2'' ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon disulfide (( CS_2 ))</td>
<td>45 deg</td>
<td>( I=2 \times 10^{18} \text{ W/m}^2 )</td>
<td>11.91</td>
<td>3.404 deg = ( \theta_2' )</td>
<td>1.578 deg</td>
</tr>
<tr>
<td></td>
<td>45 deg</td>
<td>( 2I )</td>
<td>22.19</td>
<td>1.827 deg = ( \theta_2'' )</td>
<td></td>
</tr>
<tr>
<td>silicon dioxide (( SiO}_2 ))</td>
<td>45 deg</td>
<td>( I=2 \times 10^{18} \text{ W/m}^2 )</td>
<td>1.512</td>
<td>27.883 deg = ( \theta_2' )</td>
<td>1.041 deg</td>
</tr>
<tr>
<td></td>
<td>45 deg</td>
<td>( 2I )</td>
<td>1.566</td>
<td>27.842 deg = ( \theta_2'' )</td>
<td></td>
</tr>
</tbody>
</table>
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 (KH₂PO₄ (KDP) crystal at the pick intensity of 0.6 TW/cm² 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 P₁ is taken as input beam. A detector is placed at P₂ will detect the output beam after refraction. If P₁ is absent, the light will follow a path OP₂ and will be detected by the detector due to presence of CILS. But if P₁ is present, after refraction, the light will follow a path other than OP₂, may be OP₃, and the detector will not detect any light signal. Thus the system acts as optical NOT gate.

III. 2 All-optical Ex-OR gate:

The two inputs all-optical XOR gate using NLM is shown in Fig 3. Here D₁ and D₂ are two input channels. A detector placed at D₃ gives the output. When only one input channel carries light signal, the light beam after refraction will detect by the detector at D₃, unless not.

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. A₀ and B₀ are the two binary input beams. Designate the minuend bit by A₀ and the subtrahend bit by B₀. CILS, a probe beam, is used here to act NG block as NOT gate. Two detectors placed at C₀ and D₀ gives the outputs. Light at D₀ indicates the DIFFERENCE. Also the light at C₀ 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 A₀ = 0 and B₀ = 0. At P₁ from NG we get the complemented output of A₀ due to the presence of CILS (i.e. P₁ = A₀). P₁ and B₀, the two inputs of AND gate (AG), now become 1 and 0 respectively. As a consequence the output C₀ (BORROW) will be 0. On the other hand, as both the inputs of the EX-OR gate (EG) are 0 the output D₀ 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 A₀ = 0 and B₀ = 1. It means A₀ is less than B₀ 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).

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 \( O_2P_1 \) path, \( P_1 \) is equal to 0 (\( = A_0 \)). 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

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_0 )</td>
<td>( B_0 )</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### 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. 4: All-optical half-subtractor](image-url)

![Fig. 5: All-optical full-subtractor](image-url)
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

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_n )</td>
<td>( B_n )</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

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 \( O_1E_i \) 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 severely 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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REFERENCES


