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All-Optical Implementation of Arithmetic Operation Scheme using Optical Nonlinear Material Based Switching Technique

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Abstract

Nonlinear material based all-optical switching mechanism is utilized here to develop the all-optical arithmetic operation scheme. Analog optical signals are converted to the corresponding digital signals by optical tree architectures. First a four bit arithmetic unit has been accessed which is elevated to a higher bit arithmetic unit in course. These circuits can execute innumerable arithmetic operations and remarkably, as they are all-optical and fully parallel in nature. These all-optical arithmetic units can gear up to the highest capability of optical performance in high-speed all-optical computers.

Keywords

Optical Switching; All-optical EX-OR Gate; All-optical Parallel Adder; All-optical True/complement-one/zero Circuit; All-optical Arithmetic Circuit

Introduction

Today computer has become a part and parcel of modern life and undeniably it has brought about a sea change in our life style. As life becomes faster day by day and computer widens its globe, computers with more computing speed are needed to be designed. The speed specially depends upon the speed of arithmetic operation, an essential task in any computing scheme. Existing electronic arithmetic circuits by Very Large Scale Integration (VLSI) technology cannot beat this challenge to achieve very high speed (above GHz) operations and data processing. To cope with the soaring demands of achieving a processing speed greater than the limit of 10^9 logical operations per second there is no way but to replace electronics with photonics. In photonics, 'photon', an uncharged particle, is used as signal carrier in lieu of 'electron'. The idea of introducing light signal as carrier in photonics for information processing has been used over the last few years, primarily because of the advantages of parallelism, high speed, high bandwidth and no cross talk, low transmission loss. Also optical devices are compact, lightweight, inexpensive to manufacture and more facile with stored data than conventional magnetic materials. In view of these promising features, optical data processing and computation has created major interest among scientists and engineers in the field of optical computation and communication. Several techniques have been proposed and developed to implement various logic, algebraic, arithmetic and image operations in optical domain. In the recent past all-optical switching mechanism by nonlinear optical material established its validity as one of such hopeful techniques. The proposal of employing such unique technique to design and develop various digital circuits is of great attention to the modern photonics community.

The optical implementations of several arithmetic units have been attempted using different techniques such as using tree architecture by proper accommodation of optical nonlinear materials, using bit-WDM, arithmetic units by a single liquid-crystal display panel, optical shadow casting technique. Some of them are hybrid in nature that limits their efficiency in terms of speed. In other proposals they can perform a few arithmetic operations. Some don't have any well defined overflow condition. Some have both the above mentioned problems. The paper presents a scheme for the all-optical implementation of arithmetic operational circuit with proper use of nonlinear material-based all-optical switching mechanism. An all-optical Full-Adder is designed first. It is extended to form an all-optical four bit Parallel-Adder. Next the all-optical true/complement-one/zero circuit is logically designed. Finally we combine these two circuits to develop a four bit arithmetic operation scheme. As the circuit is purely all-optical in nature, it is very simple and very fast. Several arithmetic operations can be achieved with extreme accuracy and well-defined overflow. The scheme can be extended to a higher bit arithmetic operation scheme easily. An ALU of our long-cherished desire, an optical computer, can be implemented including this scheme.

All-optical Switching Behavior of Nonlinear Material and Its Uses as All-optical EX-OR Gate

The phenomenon photorefractivity 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. If we consider Maxwell's equation in a medium, nonlinear optical effects take place provided the polarization is the outcome of higher-order (nonlinear!) terms in the field:

$$P = \varepsilon_0 \left[\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \right] \quad (1)$$

Where;

P = induced polarization of medium

ε_0 = dielectric constant of vacuum

E = electric field

$\chi^{(i)}$ = succeptibilities of 'i' order.

The refractive index in the presence of linear and nonlinear polarization:

$$n = \sqrt{1 + \chi^{(1)} + \chi^{(2)} |E|^2} \quad (2)$$

Ignoring higher terms

Now, the usual refractive index (which we'll call n_0) is:

$$n_0 = \sqrt{1 + \chi^{(1)}} \quad (3)$$

So:

$$n = \sqrt{n_0^2 + \chi^{(2)} |E|^2} = n_0 \sqrt{1 + \chi^{(2)} |E|^2 / n_0^2} \quad (4)$$

Assume that the nonlinear term << n_0 :

So:

$$n \approx n_0 \left[1 + \chi^{(2)} |E|^2 / n_0^2 \right]^{\frac{1}{2}} \approx n_0 + \chi^{(2)} |E|^2 / 2n_0 \quad (5)$$

Usually, we define a "nonlinear refractive index", n_1:

$$n = n_0 + n_1 I \quad (6)$$

$$\text{since } I \propto |E|^2$$

Every material obeys the Eq. (6). But the materials having higher $\chi^{(2)}$ (succeptibilities of 2nd order) i.e. n_1, are considered as nonlinear materials. The refractive index of some nonlinear materials (NLM) such as carbon disulfide, pure silica, potassium dihydrophosphate (KDP), (KH_2PO_4) 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 Eq. (6). 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.

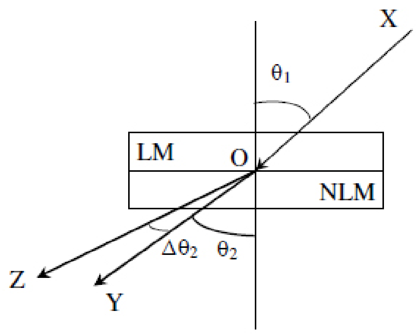

FIG. 1 INTENSITY SWITCHING OF OPTICAL NONLINEAR MATERIAL

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 (incident 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 refractive angle for different incident light intensity I_1 direction (angle of refraction θ_2). The deviation of 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 arithmetic circuit.

Equation (6) gives the expression of refractive index n, n_0 is linear term and n_1 is the nonlinear correction term. For carbon disulfide (CS_2) n_0 = 1.63, $n_1 = 514\times10^{-20}$ m²/W. and for fused silicon dioxide (SiO_2) n_0 = 1.458, $n_1 = 2.7\times10^{-20}$ m²/W. If we use CS_2 and SiO_2 as nonlinear materials and the pulse laser of intensity $I = 2\times10^{18}$ W/m² as a source, we can estimate the deviations of light in two cases as given in Table 1. All-optical logic NOT gates and EX-OR gates using such switching mechanism are already reported. These logic gates are implemented in optics 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 femto-second (fs) laser pulses and 1-mm-thick potassium dihydrophosphate crystal at the pick intensity of 0.6 TW/cm² and duration of 60 fs. M. Choi et al. showed that a single-layer terahertz metamaterial has a peak refractive index of 38.6 while maintaining low losses. It is a broadband, extremely high index of refraction going beyond the limit that is attainable with naturally existing substances, lead sulphide, strontium titanate. Using these types of nonlinear material we can get higher deviation angle than that mention in Table 1 even about nano- or micro- dimension devices. A. Ray et al. use the nonlinear material, Nd:YAG as laser cavity which prove that the intensity switching of optical nonlinear material proposed by us can be implemented successfully.

All-optical EX-OR gate

The two inputs all-optical EX-OR gate using NLM is shown in Fig 2. 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 be detected by the detector at D_3. It is not possible in other three conditions.

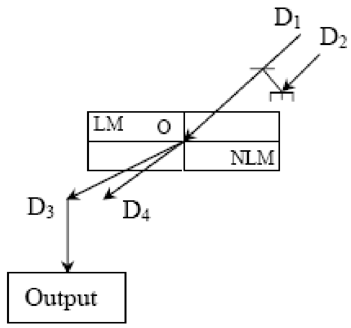

FIG. 2 ALL-OPTICAL EX-OR GATE

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/m²	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/m²	1.512	27.883 deg = θ'_2	1.041 deg
	45 deg	2I	1.566	26.842 deg = θ''_2	

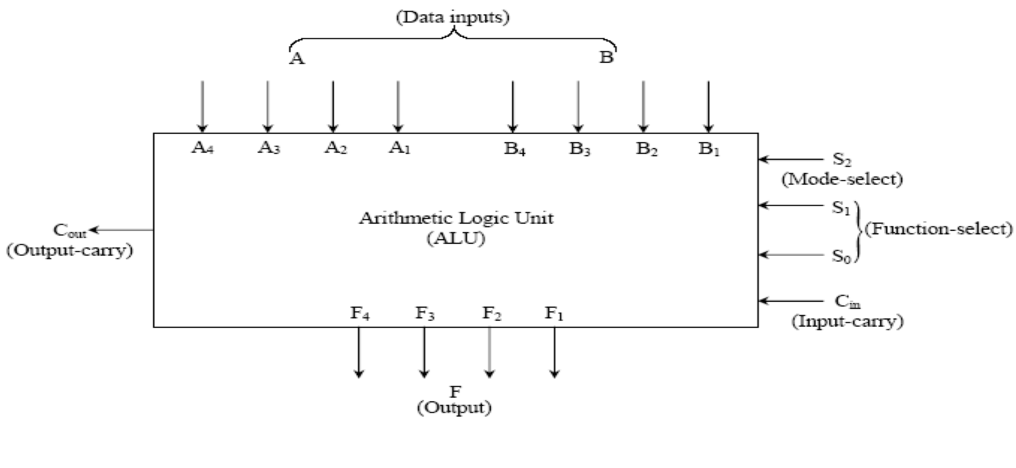

FIG. 3 BLOCK DIAGRAM OF A CONVENTIONAL FOUR-BIT ALU

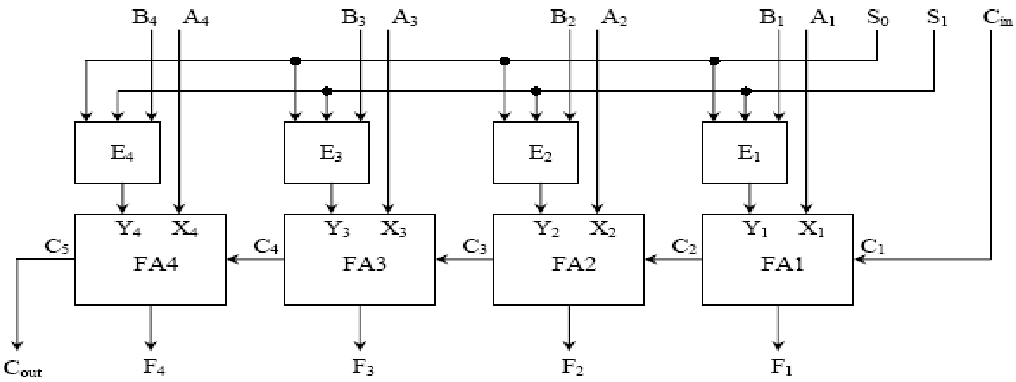

FIG. 4 ELECTRONICALLY ADDRESSED 4 BIT ARITHMETIC CIRCUIT

Conventional Electronic Arithmetic Circuit in ALU

The block diagram of a 4-bit conventional ALU is shown in Fig. 3. If S_2 = 0 ALU acts as arithmetic unit. The fundamental element of the arithmetic section of an ALU is a parallel adder. By controlling the one set of data inputs to a parallel adder, it is possible to obtain several types of arithmetic operations. The input carry, C_{in} enters into the first full-adder circuit (LSB position). The function-select inputs, S_1 and S_0 which control the one set of data input externally to a parallel adder, specify the particular arithmetic operation to be generated. C_{in} is used as third selection variable that can double the number of arithmetic operations. Fig. 4 show block diagram of electronic four bit arithmetic circuit. The E1, E2, E3, E4 are electronically addressed four true/complement, one/zero circuits. FA1, FA2, FA3 and FA4 are four full-adders connected to form a four bit parallel adder. Here the four data inputs (A_4, A_3, A_2 and A_1) from A are combined with the four data inputs (B_4, B_3, B_2 and B_1) from B to produce an arithmetic operation at the F (= $F_4F_3F_2F_1$) outputs.

Optical Tree Architecture

Tree architecture in optics is a powerful arrangement which can change a decimal optical signal to its respective binary value and vice versa. In our present proposal we use it to convert an analog optical signal to its binary (digital) counterpart. A brief representation of it has been made in Fig. 5 by converting the decimal values from 0 to 3. The decimal values 0, 1, 2 and 3 are marked against four light beams shown by NA_1, OA_2, PB_1 and QB_2 respectively. In this figure the abbreviation BS stands for Beam Splitter and M for Mirror. Now, there are two coupling arrangements in F block and only one in F′ block. The light rays NA_1 and OA_2 are coupled by a beam splitter and a mirror to form a single beam A_3A_4. In the similar fashion, PB_1 and QB_2 beams are coupled by a beam splitter and a mirror to form a single beam B_3B_4. These two couplings are done in F block. The beam splitter and the mirror combination in F′ block further couples the output beams A_3A_4 and B_3B_4 from F block to form the main light beam A_5R. The binary bits X_2X_1 yield the output of the system which is the binary equivalent of any decimal number from 0 to 3. The lower bit of the result X_1 is enlightened by the beam splitter from NA_1 and OA_2 beams. X_2, the upper bit, is obtained from another beam splitter placed on the light beam B_3B_4. For illustration we allow a light beam through PB_1 which indicates that the input is a decimal number 2. Then we always get light at X_2 terminal after reflection from BS on B_3B_4 and X_1 remains dark. As a result, X_2X_1 represents 10, which is nothing but the binary equivalent of the decimal number 2. We can expand this system to a higher scheme, from which one can get the binary equivalent of any large decimal number by simply following the principle narrated in Fig. 5.

All-optical Full Adder and Parallel Adder

All-optical full adder can add 3 digits at a time and has three inputs and two outputs. The outputs are entitled as SUM and CARRY-OUT. For addition of two multi-bit numbers, we need several full adders connected in parallel. Chowdhury et al designed an adder circuit connected in parallel. In that circuit they used a half adder to get addition operation in the LSB position. These circuits are very similar to the conventional electronic circuit. But if we replace it by an all-optical full adder, then there is a provision of an extra input say ‘Carry-in’ input which has great importance in designing arithmetic circuit.

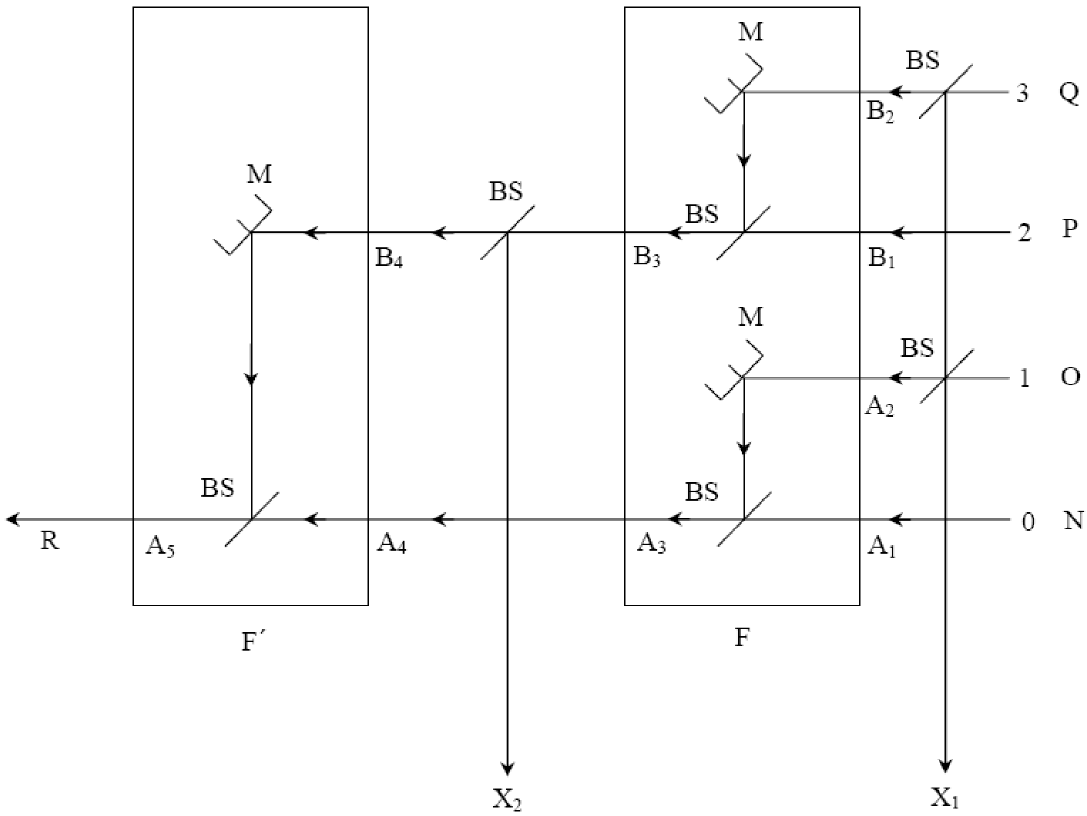

FIG. 5 OPTICAL TREE ARCHITECTURE

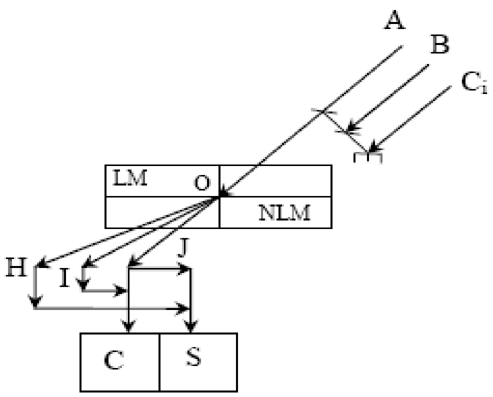

FIG. 6 ALL-OPTICAL FULL ADDER

All-optical Full Adder

The LM-NLM block acts as full adder as depicted in Fig. 6. Here A, B and C_i are the three inputs of the all-optical full adder circuit. The input A and B are the two bits which are to be added and C_i, the third input, comes from the carry generated by the previous addition. The input C_i stands for Carry-in. If any one of the three light beams AO, BO and C_iO brings light, after refraction the light will pass through OH direction. When any two of A, B and C_i are logical 'one', then light will appear at I terminal. OJ direction carries light signal if there is light in all the three input channels. The light from OH direction indicates the SUM (S) and light from OI channel represents the CARRY-OUT (C). Again, light at J point indicates the presence of both SUM and CARRY-OUT bit. The detector S detects the SUM and C detects the CARRY-OUT bit. These are the final outputs of the all-optical full adder circuit.

All-optical Parallel Adder using 'carry-in' input

For simplification we may take a system in Fig. 7(B) which can add two four bit binary numbers A (= $A_4A_3A_2A_1$) and B (= $B_4B_3B_2B_1$). We can add two decimal numbers by the scheme when we affix the optical tree architecture, which can convert a decimal number to its equivalent binary one, before the binary parallel adder as in Fig. 7(A). Still the output is in binary state. If we want the result of the summation operation in decimal state, another optical tree architecture arrangement which can convert a binary number to its decimal equivalent, should be attached after the binary parallel adder. Four full adders, made of with the combination of LM and NLM, are needed to implement the four bit all-optical parallel adder.

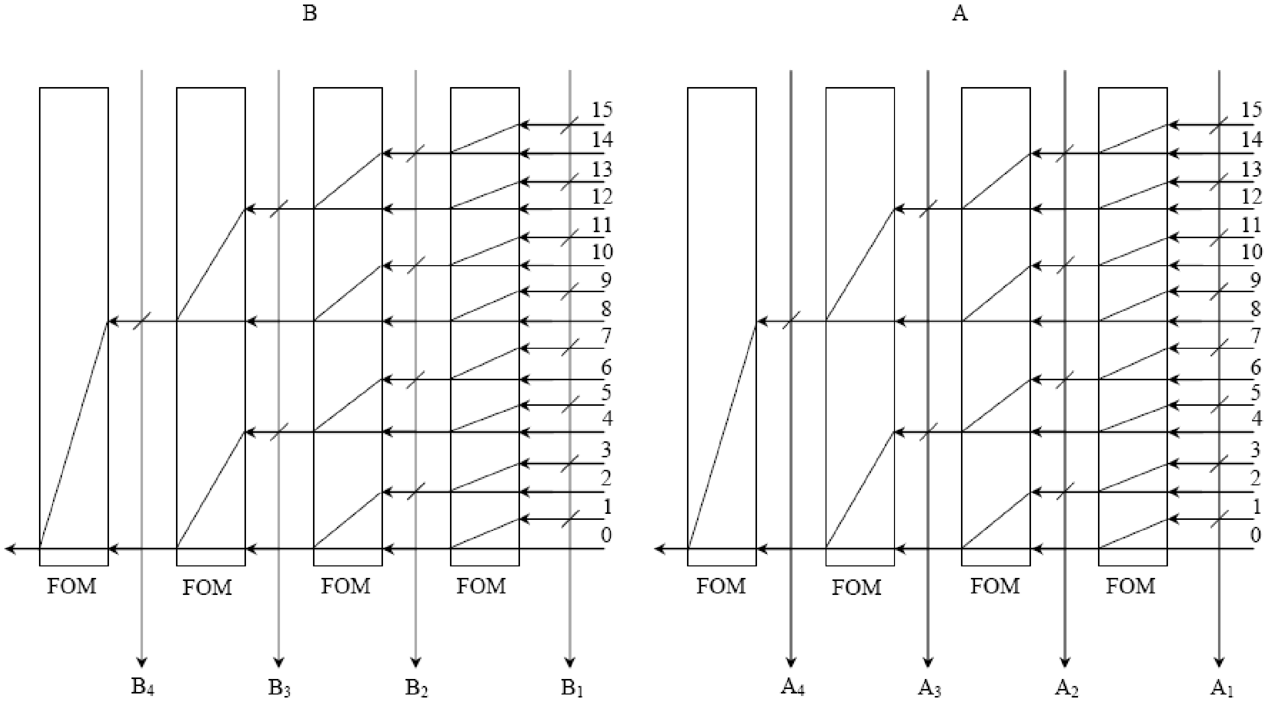

FIG. 7(A) ALL-OPTICAL DECIMAL TO BINARY CONVERTER AS INPUT TO 4 BIT PARALLEL ADDER CIRCUIT

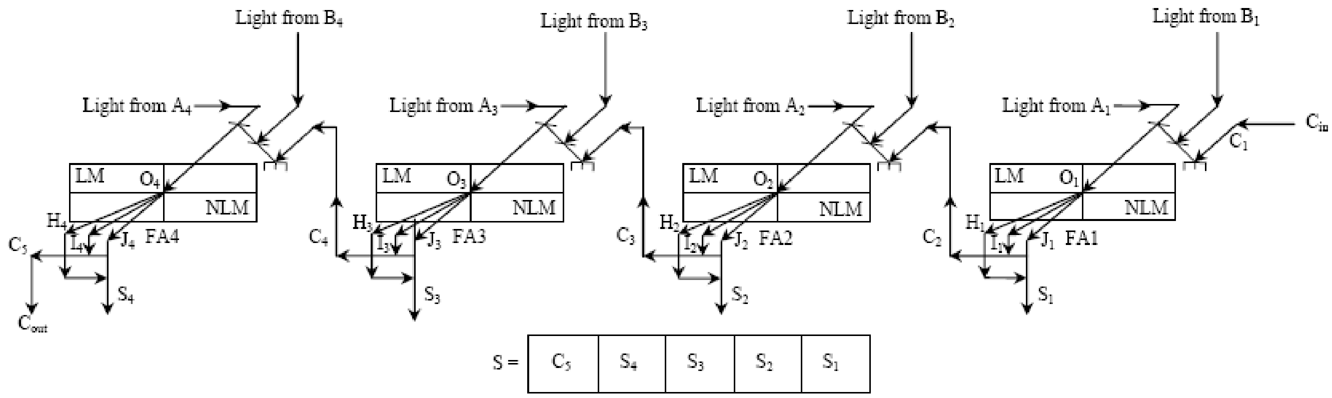

FIG. 7(B) ALL-OPTICAL 4 BIT PARALLEL ADDER CIRCUIT

For the first full adder block (FA1), A_1 and B_1 are the two inputs and the third input C_{in} will remain as unused lead. A_2, B_2, C_2; A_3, B_3, C_3 and A_4, B_4, C_4 are the three inputs of second, third and fourth full adder (FA2, FA3, FA4) respectively. C_2, C_3, C_4 and C_5 are the CARRY-OUT bits from FA1, FA2, FA3 and FA4 respectively. The SUM outputs of the four full adders (FA1, FA2, FA3 and FA4) are indicated as S_1, S_2, S_3 and S_4 correspondingly. $C_5S_4S_3S_2S_1$ is the final output result i.e., we can say, the summation of $A_4A_3A_2A_1$ and $B_4B_3B_2B_1$ is $C_5S_4S_3S_2S_1$.

To realize the mechanism of the all-optical parallel adder let us consider a case of adding 13 and 12 i.e. A ($A_4A_3A_2A_1$ = 1101) = 13 and B ($B_4B_3B_2B_1$ =1100) = 12. The two inputs of the first full-adder (FA1) are A_1 = 1 and B_1 = 0. The third input is $C_1 = C_{in} = 0$ because it is unused. The output light will traverse along O_1H_1 path after refraction from FA1. As a result SUM = 1 and CARRY-OUT = 0 i.e. S_1 = 1, C_2 = 0. Now, the inputs of the second full adder, FA2 are A_2 = 0, B_2 = 0 and C_2 = 0 (CARRY-OUT from FA1) i.e. all the input channels remain dark. So the outcomes of FA2 are S_2 = 0 and C_3 = 0. Next, A_3 is equal to 1, B_3 is equal to 1 and the CARRY-OUT of FA2, C_3 is equal to 0. All these are inputted to the third block FA3. As two of the inputs are lightened, only O_3I_3 will carry light. This indicates S_3 remains at low state. The CARRY-OUT (C_4) turns at high state which will farther feed to the 'carry-in' input of the final full adder block FA4. The other two inputs of the final fourth full adder are $A_4 = 1$ and $B_4 = 1$. It means that all the three inputs have light signal. As a consequence, light will appear at J_4 terminal while passing through FA4. Therefore, $S_4 = 1$ and $C_5 = 1$. So the final result is $C_5S_4S_3S_2S_1$ = 11001. The decimal equivalent of 11001 is 25, which comes from the addition operation of 1101 (= 13) and 1100 (=12).

All-optical true/complement-one/zero circuit

A parallel adder circuit can perform several arithmetic operations as shown in Table 2. According to Table 2, to obtain different types of arithmetic operations from a parallel adder, it is essential to control a set of data with another external circuit. We design an all-optical circuit for the true/complement, one/zero operation in an all-optical arithmetic operation scheme. This circuit is illustrated in Fig.8. It is a powerful all-optical circuit that controls the input of each B terminal externally by the two selection lines S_1 and S_0 to provide the functions shown in Table 2. One typical input named as B_i and an output by Y_i are depicted in the diagram.

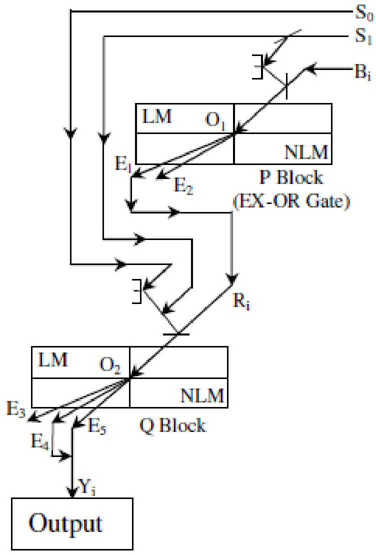

FIG. 8 ALL-OPTICAL TRUE/COMPLEMENT-ONE/ZERO CIRCUIT

TABLE 2 OPERATIONS OBTAINED BY CONTROLLING EXTERNALLY ONE SET OF INPUTS (B) TO A PARALLEL ADDER (A = A AND $S_2 = 0$)

Function-select S_1	Function-select S_0	Controlled Inputs at	Input carry $C_{in} = 0$	Input carry $C_{in} = 1$
0	1	B	A, B → Parallel adder ← $C_{in} = 0$; C_{out}; F = A + B; (2) Addition	A, B → Parallel adder ← $C_{in} = 1$; C_{out}; F = A + B+1; (3) Addition with carry
1	0	$\bar{B}$	A, $\bar{B}$ → Parallel adder ← $C_{in} = 0$; C_{out}; F = A + $\bar{B}$; (4) A plus 1's complement of B	A, $\bar{B}$ → Parallel adder ← $C_{in} = 1$; C_{out}; F = A + $\bar{B}$ + 1; (5) Subtraction
0	0	0	A, 0 → Parallel adder ← $C_{in} = 0$; C_{out}; F = A; (0) Transfer A	A, 0 → Parallel adder ← $C_{in} = 1$; C_{out}; F = A + 1; (1) Increment A
1	1	All 1's	A, All 1's → Parallel adder ← $C_{in} = 0$; C_{out}; F = A - 1; (6) Decrement A	A, All 1's → Parallel adder ← $C_{in} = 1$; C_{out}; F = A; (7) Transfer A

The circuit contains two LM-NLM blocks, P block (EX-OR gate) and Q block. Here S_1, S_0 and B_i are the three inputs of the circuit. Y_i is the final output of it. S_1 and B_i are the two inputs of the EX-OR gate (P block). R_i (= E_1), the output of the P block, S_1 and S_0 are the three inputs of the Q block.

Let us discuss the truth table of the all-optical true/complement-one/zero circuit.

Let S_1 and S_0 both be inactive (i.e., $S_1 = S_0 = 0$), then two cases may arise. Case 1: if $B_i = 0$ then $E_1 = R_i = 0$ and all the three inputs of Q block are 0 which yields $Y_i = 0$. Case 2: if $B_i = 1$ then $E_1 = R_i = 1$. At Q block, as only R_i has light signal, photons travel along O_2E_3 direction (i.e. $Y_i = 0$). In both the cases the output of this circuit, $Y_i = 0$. We can say that for $S_1 = S_0 = 0$ the output, Y_i is equal to 0 independent of the input B_i.

Now, we consider that $S_1 = 0$ and $S_0 = 1$. There will be two possibilities. 1: if we take $B_i = 0$, all the inputs to P block remain dark and also E_1 (= R_i = 0) has no light. In the next stage the inputs are $S_0 = 1$, $S_1 = R_i = 0$. As a result we can get light at E_3 terminal after refraction by Q block i.e. $Y_i = 0$. 2: again if we take $B_i = 1$, after refraction by P block, the path, O_1E_1 carry light. It indicates that in the next stage the inputs are $S_1 = 0$, $S_0 = R_i = 1$. As a result one can get light at E_4 terminal i.e. $Y_i = 1$. In the two possibilities Y_i is nothing but B_i, for $S_1 = 0$ and $S_0 = 1$.

In this condition, S_1 may be assumed active and S_0 inactive which means $S_1 = 1$, $S_0 = 0$. First of all, B_i (=0) input is at low state. The output of the P block, E_1 (= R_i) turns into logical '1' state. Now, as two of the inputs $S_1 = R_i = 1$ but $S_0 = 0$, the final output, Y_i becomes active i.e. $Y_i = 1$. On the other hand, B_i (=1) input is at logical 1 state. The output of the P block, E_1 (= R_i) does not change its state. Now, as two of the inputs S_0 and R_i remain inactive but S_1 is active, the light will follow the path O_2E_3 that yields the final output, $Y_i = 0$. For both $B_i = 0$ ($Y_i = 1$) and $B_i = 1$ ($Y_i = 0$) the final output Y_i complements the input B_i ($Y_i = \overline{B}$).

Finally, we take the last possible function-select inputs $S_1 = 1$ and $S_0 = 1$. Firstly we think that $B_i = 0$. As $S_1 = 1$, light will travel O_1E_1 direction when passing through the EX-OR block. It indicates that $E_1 = R_i = 1$. Now, all the three input channels of Q block carry light signal. As a consequence, the path O_2E_5 has light signal. The detector detects light. So, the final output Y_i equals to1. Secondly, we suppose that B_i is at high state. As both the inputs $B_i = 1$ and $S_1 = 1$, light will travel O_1E_2 direction when passing through the P block. It indicates that $E_1 = R_i = 0$. Now, as two (S_1 and S_0) of the three input channels of Q block bring light signal, the path O_2E_4 carries light signal. The detector detects light. So, the final output $Y_i = 1$. As a result we can say that for $S_1 = S_0 = 1$ the output, Y_i is equal to 1, independent of the input B_i.

The truth table for an all-optical true/complement-one/zero circuit is narrated in Table 3.

TABLE 3 TRUTH TABLE OF AN ALL-OPTICAL TRUE/COMPLEMENT-ONE/ZERO CIRCUIT

Inputs			Outputs			State
S_1	S_0	B_i	R_i	Y_i		
0	0	0	0	0	}0	zero
		1	1	0		
0	1	0	0	0	}B_i	true
		1	1	1		
1	0	0	1	1	}$\overline{B_i}$	complement
		1	0	0		
1	1	0	1	1	}1	one
		1	0	1		

All-optical Arithmetic Circuit

We now design the all-optical four bit arithmetic circuit as shown in Fig 9. Here the four data inputs (A_4, A_3, A_2 and A_1) from A are combined with the four data inputs (B_4, B_3, B_2 and B_1) from B to generate an arithmetic operation at the F (= $F_4F_3F_2F_1$) outputs. If we want to input decimal data in this scheme, we must add optical tree architecture A and B which can convert a decimal number to its equivalent binary one before the circuit. The two function-select inputs S_1 and S_0 identify the particular arithmetic operation to be generated. C_{in}, the input-carry in the least significant position of a parallel adder, is used as third selection variable that can double the number of arithmetic operations. In this way, it is possible to create a total of eight arithmetic operations by total three selection variables S_1, S_0 and C_{in}. The circuit is constructed by twelve LM-NLM blocks. The combinations of P_1, Q_1 blocks; P_2, Q_2 blocks; P_3, Q_3 blocks and P_4, Q_4 blocks form the four all-optical true/complement-one/zero circuits to control B_1, B_2, B_3 and B_4 from one set of data input B. According to the value of S_1S_0, the inputs B_1, B_2, B_3 and B_4 become Y_1, Y_2, Y_3 and Y_4 respectively by the four all-optical true/complement-one/zero circuits. The four full-adders FA1, FA2, FA3 and FA4 are connected with each other to form a parallel adder. The input-carry C_{in} (=C_1) goes to the full-adder in the least significant bit position. The output-carry C_{out} (=C_5) comes from the full-adder circuit in the most significant bit position.

The output-carry from one full-adder becomes the input-carry of the next full-adder. X_1 (= A_1), Y_1; X_2 (= A_2), Y_2; X_3 (= A_3), Y_3 and X_4 (= A_4), Y_4 are the other two inputs of the four full-adders FA1, FA2, FA3 and FA4 respectively. $F_4F_3F_2F_1$ is the final output result i.e. we may conclude that the particular operation (for a particular possible value of $S_1S_0C_{in}$) between $A_4A_3A_2A_1$ and $B_4B_3B_2B_1$ is $F_4F_3F_2F_1$. Therefore in Fig. 9 the inputs of the Arithmetic Circuit are A and B. But the inputs of the Parallel Adder Circuit are X and Y. For all eight operation of Table 2 & 4 X = A. But Y varies with the function-selection variables s_1 and s_0. For $s_1 = 0$ and $s_0 = 0$, Y = 0 in 1st and 2nd rows of Table 4. When $s_1 = 0$ and $s_0 = 1$, Y = B in 3rd and 4th rows of Table 4. In 5th and 6th rows of Table 4 for $s_1 = 1$ and $s_0 = 0$, Y = $\overline{B}$. For $s_1 = 1$ and $s_0 = 1$, Y = all 1's in 7th and 8th rows of Table 4.

All eight arithmetic operations are shown at different position (0, 1, 2, ….. 6, 7) in Table 2. The arithmetic addition of A and B is done when $Y_i = B_i$ (i = 1, 2, 3 and 4) and there is no light signal at C_{in} terminal. The function-select inputs are S_1 and S_0. S_1 has no light and S_0 has light that creates the condition $Y_i = B_i$ for all i's. This is shown in Table 2-(2). Only by enlightening C_{in}, we obtain F = A + B + 1 as in Table 2-(3) . Now we think the effect of complementiong all the bits of input B these are shown in next two operations in Table 2-(4 and 5) respectively. This (Y = $\overline{B}$) can be doen by making $S_1 = 1$ and $S_0 = 0$. The output F yields A + $\overline{B}$ when C_{in} point remains dark. i. e. A + { $\overline{B}$ } = A + {(2's complement of B) – 1} = A + {(– B) – 1} = A – B – 1. This operation is nothing but the sum of A and 1's complement of B. This operation is similar to a subtraction with BORROW opration (i.e. = A – B – 1) if the output carry is discarded. Adding 1 to this sum by passing light through C_{in} (=1) end F (= A + $\overline{B}$ + 1) produces the summation of A and 2's complement of B. In sign 2's complement arithmetic F = A + $\overline{B}$ + 1 = A + (– B) = A – B that is nothing but subtraction operation if C_{out} (= C_5) is ignored as in Table 2-(5). If both the function-select inputs S_1 and S_0 stay at low state, all the digits Y_1, Y_2, Y_3 and Y_4 become dark and F turns to A (A + 0). By making $C_{in} = 1$ we acquire the increment operation (i.e. F = A + 1) as in Table 2-(1). The decrement operation F = A – 1 is achieved by passing light through each Y_i terminal that means $Y_1Y_2Y_3Y_4 = 1111$. The essential condition for this is that both the inputs S_1 and S_0 should carry light signal. Here if C_{out} carry light, the four bit parallel adder represents the binary number 10000 (= 2^4). Also we know that, 10000 – 1 = 1111 (= $2^4 – 1$). Adding $2^4 – 1$ to A, we get F = A + 2^4 – 1 = 2^4 + A – 1. If the output-carry 2^4 is discarded, we get F = A – 1. If we change the state of C_{in} from low to high, F will be equal to (A – 1 + 1 =) A. From this above description and from Table 2 and 3 the function table for the all-optical arithmetic circuit can be drawn which is shown in Table 4.

Let us examine the operations of the all-optical arithmetic circuit which is doen in sign 2's complement arithmetic. So, let us take a simple example of A = $(–7)_{10}$ and B = $(–3)_{10}$ which two numbers exhibit different arithmetic operations with different values of $S_1S_0C_{in}$. In Fig 7(A) at A light will force through beam marked as 9, as a result one can get light only at A_4 and A_1 terminals. On the other hand at optical tree architecture B light will allow to pass through the line having number 13. Light will present at all the other output terminals except B_2. So we have $A_4A_3A_2A_1$ (=$X_4X_3X_2X_1$) = $(1001)_2$ and $B_4B_3B_2B_1$ = $(1101)_2$ which are the sign 2's complement number representation of the two decimal numbers $(–7)_{10}$ and $(–3)_{10}$ respectively. The first bit stands for sign of the number and the rest 3-bit represent the magnitude of the number in 2's complement representation. One set of inputs of the parallel adder, $X_4X_3X_2X_1$(=$A_4A_3A_2A_1$) is equal to 1001 for all the different values of $S_1S_0C_{in}$.

As the three selection variables S_1, S_0 and C_{in} are there, eight possibilities may occur.

If we take the situation that two function-select inputs S_1 and S_0 are at logical 0 state, then $Y_4Y_3Y_2Y_1 = 0000$ i.e. none of Y inputs has light. This is true even when $C_{in} = 0$ or $C_{in} = 1$ as presented in the first and second condition respectively.

In this condition C_{in} is equal to 0. The first full adder (FA1) has inputs $C_{in} = 0$, $X_1 = 1$ and $Y_1 = 0$. The beam O_1H_1 carries photons because only one of the inputs is at high state. There will be light at F_1 (= 1) and no light at C_2 (= 0). Now as inputs $C_2 = X_2 = Y_2 = 0$ (for FA2), the outputs F_2 and C_3 remain dark. The three inputs and two outputs of the third full adder FA3 stay low as FA2. The light signal will follow the path O_4H_4 after refraction from FA4 block because only X_4 carries light signal and Y_4 and C_4 carry no light. It indicates that $C_5 = C_{out} = 0$ and $F_4 = 1$. Finally we obtain F (=$F_4F_3F_2F_1$) = 1001 which is same as A. There is no output carry. We conclude that the circuit performs the transformation of input A when all the selection variables are at low state.

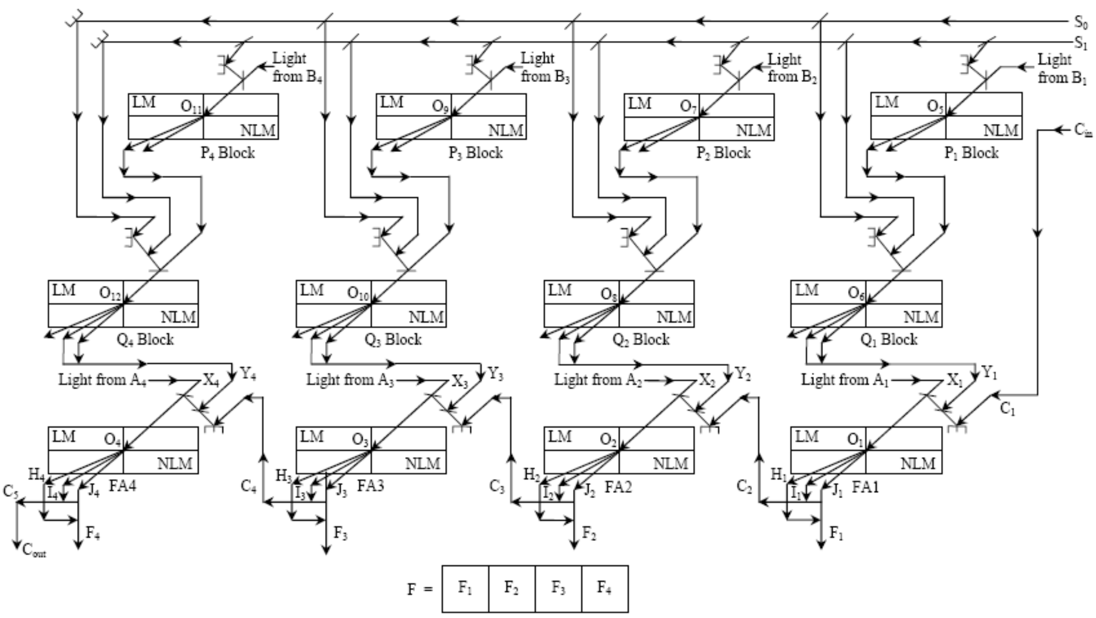

FIG. 9 ALL-OPTICAL 4 BIT ARITHMETIC CIRCUIT

TABLE 4 FUNCTION TABLE FOR THE ALL-OPTICAL ARITHMETIC CIRCUIT

Function-selection variables			Y equals to	Output equals to	Circuit action
S_1	S_0	C_{in}			
0	0	0	0	F = A	Transfer of A
0	0	1	0	F = A + 1	Increment of A
0	1	0	B	F = A + B	Addition of B to A
0	1	1	B	F = A + B +1	Addition of B to A plus 1
1	0	0	$\overline{B}$	$A+\overline{B}$ = A-B-1	Addition of 1's complement of B to A means Subtraction of B with BORROW from A
1	0	1	$\overline{B}$	$A+\overline{B}+1$ = A-B	Addition of 2's complement of B to A means Subtraction of B from A
1	1	0	All 1's	F = A – 1	Decrement of A
1	1	1	All 1's	F = A	Transfer of A

In this condition, C_{in} may be assumed active i.e. $C_{in} = 1$. The first full adder (FA1) gets inputs $C_{in} = 1$, $X_1 = 1$ and $Y_1 = 0$. The direction O_1I_1 carries photons because only two of the inputs are at high state. There will be no light at F_1 (= 0) output and light at C_2 (= 1) output. Now as inputs $C_2 = 1$ and $X_2 = Y_2 = 0$ (for FA2), the output F_2 changes its state to 1 and C_3 remains at 0 state. The three inputs and two outputs of the third full adder (FA3) stay at low state. The light will go through the path O_4H_4 after refraction from FA4 block because only X_4 carries light signal and Y_4 and C_4 do not carry any light. It indicates that $C_5 = C_{out} = 0$ and $F_4 = 1$. Finally we obtain F ($=F_4F_3F_2F_1$) = 1010 (= $(-6)_{10}$) which is same as A + 1 (–7 + 1). There is no output carry. Now, we may conclude that the circuit performs the increment of 'A' input, when all the function-select variables are at low state except C_{in}.

After that we take the condition while two function-select inputs $S_1 = 0$ and $S_0 = 1$. As a result, $Y_4Y_3Y_2Y_1$ = 1101 (i.e. Y = B) which are to be input to the parallel adder. The value of Y is true though C_{in} takes the value 0 and 1 in the third and fourth condition respectively.

Thirdly we take $C_{in} = 0$ and then the first full adder (FA1) has inputs $C_{in} = 0$, $X_1 = 1$ and $Y_1 = 1$. The beam O_1I_1 carries light because only two of the inputs are at high state. There will be no light at F_1 (= 0) and light at C_2 (= 1). Now as inputs $C_2 = 1$, $X_2 = Y_2 = 0$ (for FA2), the output F_2 alters its state from dark to bright and C_3 remains dark. The three inputs of the third full adder FA3, $C_3 = 0$, $X_3 = 0$ and $Y_3 = 1$. Then the output F_3 changes its state but C_4 does not. The light signal will follow the path O_4I_4 after refraction from FA4 block because only C_4 does not carry light signal. It indicates that $C_5 = C_{out} = 1$ and $F_4 = 0$. We obtain F ($=F_4F_3F_2F_1$) = 0110. There is 1 as output-carry. With the output-carry finally we get $C_5F_4F_3F_2F_1$ = 10110 (= $(-10)_{10}$) which is same as A + B $((-7)_{10} + (-3)_{10} = (-10)_{10})$. So the conclusion appears that the circuit performs the addition of two data inputs, A and B when $S_1 = 0$, $S_0 = 1$ and $C_{in} = 0$.

Now C_{in} may be taken as at high state i.e. $C_{in} = 1$. At that moment all the three inputs and the two outputs of FA1 carry light. As a consequence we have $F_1 = C_2 = 1$. The remaining three full adders, FA2, FA3 and FA4 change states following the third condition. We obtain F $(=F_4F_3F_2F_1) = 0111$. There is 1 as output-carry. With output-carry finally we receive $C_5F_4F_3F_2F_1 = 10111$ $(= (-9)_{10})$ which is same as A + B + 1 $((-10)_{10} + 1 = (-9)_{10})$. We, now, may conclude that the circuit performs the addition of two data inputs, A, B and 1 when $S_1 = 0$, $S_0 = 1$ and $C_{in} = 1$.

Next we take the condition while two function-select inputs $S_1 = 1$ and $S_0 = 0$. As a result, $Y_4Y_3Y_2Y_1 = 0010$ $((+3)_{10} - 1 = (+2)_{10})$ i.e. only one (Y_2) of Y inputs has light. Here B is complemented at Y (i.e. Y = $\overline{B}$ = 2's complement of B minus 1). The value of Y which enters to the parallel adder, remains unchanged for $C_{in} = 0$ and $C_{in} = 1$ i.e. for both the next two conditions stated below.

Here $C_{in} = 0$. The first full adder (FA1) has inputs $C_{in} = 0$, $X_1 = 1$ and $Y_1 = 0$. The beam O_1H_1 carries photons because only one of the inputs is at high state. There will be light at F_1 (= 1) and no light at C_2 (= 0). Now as inputs $C_2 = X_2 = 0$ and $Y_2 = 1$ (for FA2), the output F_2 changes to high state while C_3 remains at low status. The three inputs and two outputs of the third full adder FA3 stay at 0 state. The light signal will follow the path O_4H_4 after refraction from FA4 block because only X_4 carries light signal and Y_4 and C_4 do not carry any light. It indicates that $C_5 = C_{out} = 0$ and $F_4 = 1$. Finally, we obtain F $(=F_4F_3F_2F_1) = 1011$ $((-5)_{10} = (-4)_{10} - 1)$ which is the result of addition of $\overline{B}$ to A while $S_1 = 1$, $S_0 = 0$ and $C_{in} = 0$. There is no output-carry.

In this situation, C_{in} may be assumed active i.e. $C_{in} = 1$. The first full adder (FA1) gets inputs $C_{in} = 1$, $X_1 = 1$ and $Y_1 = 0$. The direction O_1I_1 carries photons because only two of the inputs are at high state. There will be no light at F_1 (= 0) output and light at C_2 (= 1) output. As inputs $C_2 = 1$, $X_2 = 0$ $Y_2 = 1$ (for FA2), the output F_2 remains at 0 state. At the same time C_3 changes its state to 1. Now among the three inputs only one, C_3 carries light signal and so the direction O_3H_3 carries light to give $F_3 = 1$ and $C_4 = 0$ of the third full adder (FA3). The light will go through the path O_4H_4 after refraction from FA4 block because only X_4 carries light signal and Y_4 and C_4 carry no light. It indicates that $C_5 = C_{out} = 0$ and $F_4 = 1$. Finally we obtain F $(=F_4F_3F_2F_1) = 1100$ $((-4)_{10} = (-5)_{10} + 1)$ which is equal to A + $\overline{B}$ + 1. There is no output-carry. The result 1100 is in sign 2's complement representation. The 2's complement of the answer with a minus sign i.e. – 0100_2 will be obtained as the result of subtraction of B from A $((-7)_{10} - (-3)_{10} = (-7)_{10} + (3)_{10} = (-4)_{10})$. We can say that the circuit carries out the subtraction operation when all the function-select variables input light except S_0.

Ultimately, we take the condition when both the function-select inputs have light. As a result, $Y_4Y_3Y_2Y_1 = 1111$ i.e. all 1's. Whatever may be the input-carry, for both seventh and the final conditions, the value of Y which goes to the parallel adder remains unaffected.

TABLE 5 OPERATION TABLE FOR THE ALL-OPTICAL ARITHMETIC CIRCUIT FOR THE DATA INPUT $A_4A_3A_2A_1$ $(=X_4X_3X_2X_1) = (1001)_2$ AND $B_4B_3B_2B_1 = (1101)_2$

Input			Output				
Function-selection variables			$Y=Y_4Y_3Y_2Y_1$	$C_{out} = C_5$	$F=F_4F_3F_2F_1$	F indicates	Operation done
S_1	S_0	C_{in}					
0	0	0	0000	0	1001(=1001+0000)	A	Transfer of A
0	0	1	0000	0	1010(=1001+0000+1)	A+1	Increment of A
0	1	0	1100	1	0110(=1001+1101)	A+B	Addition of B to A
0	1	1	1101	1	0111(=1001+1101+1)	A+B+1	Addition of B to A plus 1
1	0	0	0010	0	1011(=1001+0010)	A+ $\overline{B}$ = A-B-1	Addition of 1's complement of B to A means Subtraction of B with BORROW from A
1	0	1	0010	0	1100(=1001+0010+1)	A+ $\overline{B}$ +1 = A-B	Addition of 2's complement of B to A means Subtraction of B from A
1	1	0	1111	1	1000(=1001+1111)	A-1	Decrement of A
1	1	1	1111	1	1001(=1001+1111+1)	A	Transfer of A

TABLE 6 EFFECT OF OUTPUT-CARRY IN THE ALL-OPTICAL 4-BIT ARITHMETIC CIRCUIT

Function-selection variables			Output equals to	$C_{out} = C_5 = 1$ if	Operation Suggest
S_1	S_0	C_{in}			
0	0	0	F = A		C_{out} is always 0
0	0	1	F = A + 1	$A = 1111_2$	$C_{out} = 1$ and F = 0 if $A = 1111_2$
0	1	0	F = A + B	$(A+B) \geq 10000_2$	Overflow occurs if $C_{out} = 1$
0	1	1	F = A + B +1	$(A+B) \geq 1111_2$	Overflow occurs if $C_{out} = 1$
1	0	0	$F = A + \overline{B}$	A > B	If $C_{out} = 0$, A ≤ B and F = 1's complement of (B-A)
1	0	1	$F = A + \overline{B} + 1$	A ≥ B	If $C_{out} = 0$, A < B and F = 2's complement of (B-A)
1	1	0	F = A – 1	A ≠ 0	$C_{out} = 1$ except when A = 0
1	1	1	F = A		C_{out} is always 1

Here in the following possibility, C_{in} is taken as 0 and then the first full adder (FA1) has inputs $C_{in} = 0$, $X_1 = 1$ and $Y_1 = 1$. The beam O_1I_1 carries light because only two of the inputs are at high state. There will be no light at F_1 (= 0) and light at C_2 (= 1). Now as inputs $C_2 = 1$, $X_2 = 0$ and $Y_2 = 1$ (for FA2), the output F_2 alters its state from off to on and C_3 remains at off state. In the similar fashion, the third full adder FA3 yields $F_3 = 0$ and $C_4 = 1$. After refraction from FA4 block the light signal will travel the path O_4J_4 because all the three inputs carry light signal. It specifies that $C_5 = C_{out} = 1$ and $F_4 = 1$. We obtain F $(=F_4F_3F_2F_1)$ = 1000 $((–8)_{10})$. There is 1 as output carry. Finally we get $F_4F_3F_2F_1$ = 1000 which is same as A − 1 $((–7)_{10} – 1)$. We conclude that the circuit performs the decrement of the data input, A for $S_1 = 1$, $S_0 = 1$ and $C_{in} = 0$.

In the last option, C_{in} is taken as at on state and then the first full adder (FA1) has inputs $C_{in} = 1$, $X_1 = 1$ and $Y_1 = 1$. The beam O_1J_1 carries light that gives $F_1 = 1$ and $C_2 = 1$. Now as inputs $C_2 = 1$, $X_2 = 0$ and $Y_2 = 1$ (for FA2), the output F_2 alters its state from 0 to 1 and C_3 remains at 0 state. In the pattern the third full adder FA3 brings the output $F_3 = 0$ and $C_4 = 1$. Now as all the three inputs carry light (for FA4), both the outputs F_4 and C_5 alter their states from dark to bright. It specify that $C_5 = C_{out} = 1$ and $F_4 = 1$. We obtain F $(=F_4F_3F_2F_1)$ = 1001. There is 1 as output-carry. Finally we get $F_4F_3F_2F_1$ = 1001 which is same as A. We conclude that the circuit performs the same operation as depicted in first condition. The circuit transfers A for both the situations $S_1 = 0$, $S_0 = 0$, $C_{in} = 0$ and $S_1 = 1$, $S_0 = 1$, $C_{in} = 1$.

Significance of Output Carry

The output carry of an all-optical arithmetic circuit or ALU has great important in different arithmetic operations. The output carry will be 1 (i.e. $C_{out} = 1$) when output, $F \geq 2^4$ (For 4 bit ALU). If we expand the arithmetic circuit of Fig. 9 to n bits the above condition becomes $F \geq 2^n$ to give $C_{out} = 1$. Table 6 shows the effect of output carry in different arithmetic operations. Specially for the addition operation the output carry of 1 indicates an overflow situation. It means that the sum is greater than or equal to 2^4 here (2^n for n-bit citcuit) and that the sum consists of 4 + 1 bits.

Conclusion

The proposed technique of all-optical implementation of arithmetic operation scheme is very fast (above THz) as it is fully all-optical. The light signals that are severally used, bended and fedback from the outputs by mirrors and beam splitters to make the circuits simple. This operation scheme should be the first step on our dream way to all-optical Arithmetic and Logic Unit. Along with this, the circuit, being parallel becomes remarkably fast. Proper findings of nonlinear material may be a significant issue here. Essentially input lights should be chosen properly for proper function of the system. Along with this arithmetic circuit we can fabricate optical ALU for our dream target of super fast optical computer in near future.

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