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Optical computation based on nonlinear total reflectional optical switch at the interface

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Abstract. A new scheme of binary half adder and full adder is proposed. It realizes a kind of all-optical computation which is based on the polarization coding technique and the nonlinear total reflectional optical switches.

Keywords. Optical computing; beam splitter; optical switch; polarized beams.

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1. Introduction

All-optical parallel computation is the key technology in all-optical net [1]. It is also the essential part of the optical computer [2]. Optical computing was a hot research field in the 1980s. But this work was not progressed because of material limitations [3]. It received attention again with its progression in the last decades. Today, the main research direction called quantum information and quantum computation is based on the quantum nature of photons [4]. However, from the practical point of view, it still has many difficulties to overcome, such as decoherence, dissipation, and so on [4,5]. Because of this, still a large volume of work in optical computation appears in the traditional way [1,6], as in a popular review article written by Goswami [7], some of which also involve the nonlinear effect.

This paper puts forward a new way to realize the all-optical computing which is based on all-optical switches and the polarization coding technique. It also gives an example to realize all-optical computing using optical switches.

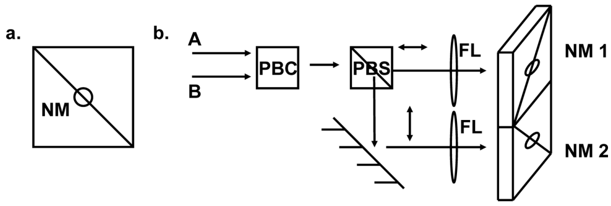

Figure 1. The optical switch and the structure of the optical router. Attention: The reflector will affect the position of polarization light beams, but the polarization light beams can still cause the nonlinear effect. NM – the nonlinear medium, FL – the focussing lens.

2. The principle of the scheme

A binary adder deals only with 0 and 1. So encoding the information based on polarization is a natural idea. In this scheme, our information is encoded on the two orthogonally polarized light beams – the horizontal polarization light beams ($\leftrightarrow$) which represent 0 and the vertical polarization light beams ($\updownarrow$) which represent 1. In addition, the circularly polarized light beams ($\bigcirc$) are used as the probe beams. Before the computation, all the inputs are prepared in the polarization state.

The key devices are the 1×2 all-optical switches which are used to control optical paths by nonlinear total reflection. They can be constructed by a pair of rectangular prisms with a nonlinear medium between them (figure 1a). In the controlling optical path, there is a focussing lens which can focus the controlling light on the nonlinear medium. Usually, the focussed controlling light will focus on the nonlinear medium at a point, which may give irreversible damage to the nonlinear media, and so the nonlinear medium should be a nonlinear liquid and the linear refractive index of the nonlinear medium (n_n) should be equal to one of the rectangular prisms (n_l). In such a situation, when there is no controlling light beams vertically shining on the nonlinear medium, the probe light will cross the optical switch along the line; otherwise, the refractive index of the nonlinear medium will decrease, and if $n_n = n_l \sin \theta_{\text{input}}$, the probe light will be totally refractive.

Therefore, using Kerr effect [8] to get this refractive index is the natural idea. However, the Kerr effect is too weak, and the refractive index cannot decrease enough [9]. Take quartz (the optical refractive material) and fullerenes (nonlinear medium) as examples [9,10]: when there is no controlling light beams shining on the nonlinear medium, $n_{\text{fullerenes}} = n_{\text{quartz}} = 1.46$ (which can be prepared by adjusting the proportion between fullerenes and toluene), then the probe light beams will transmit ahead without changing their orientations; or else, they will be reflected. In order to get total refraction, $n_{\text{fullerenes}} = n_{\text{quartz}} \sin 45^\circ = 1.03$. It means that the nonlinear liquid medium should convert into gas.

As a result, the nonlinear liquid should have the following characteristics: large nonlinear coefficient, high reverse saturated absorption property, large thermo-optic coefficient and low viscosity. Because the large nonlinear coefficient can focus the light energy, high reverse saturated absorption property will ensure that the energy can be absorbed as much as possible, at the same time, the large thermo-optic coefficient will enforce the Kerr effect. So the nonlinear liquid will convert into gas at a short time. Moreover, if no light beam is acting on the nonlinear medium, it can resume the initial condition for the low viscosity. This kind of optical switch has been independently realized by Li *et al* [9,10] and Lawson *et al* [11]. In addition, a similar optical switch using only Kerr effect was invented by Deshazer *et al* in 2001 [12].

3. The main physical resources

According to refs [10,11], the main physical resources required are as follows:

1. Sources of the polarization light beams (which are used to prepare the linear polarization light beams). The controlling light can be the Nd:YAG laser pulses (532 nm) with the maximum power density $I_0 = 1 \times 10^6$ W/cm^2. And the probe light can use the semiconducter laser pulses (747 nm) with the maximum power density $I_{\rm p0} = 5 \times 10^{-2}$ W/cm^2.
2. Polarization cubes (which can combine two polarizations as well as split them). When they are used to combine polarizations, they are called polarization beam combiners (PBC); when they are used to split polarizations, they are named polarization beam splitters (PBS).
3. Beam splitters (which allow part of the beams to pass through while reflecting the other part).
4. Polarizers (which convert the circularly polarized light beams to linear polarization light beams).
5. Nonlinear medium optical switches (which can be constructed as in §2).
6. Focussing lens.

With a view towards actual technology, this list is deliberately practical.

4. All-optical adder scheme

A binary full adder has three inputs (A, B, E) and two outputs (C, D). A and B represent the bit to be added, E is the carry bit from the previous bit addition, C is the sum output and D is the carry output.

4.1 *The designing of the half adder*

Our half adder is composed of the controlling terminal and the calculational terminal as shown in figures 1b and 3 respectively. The controlling terminal is composed of a polarization beam combiner, a polarization beam splitter and two nonlinear medium optical switches. The working process is designed as follows: firstly, the input polarized light beams A and B are mixed in a PBC. Then, the 'mixed light beams' will pass though a PBS. By this way, the horizontal polarization light beams and the vertical polarization light beams in the 'mixed light beams' will be separated. Finally, the horizontal polarization light beams will cause nonlinear effect

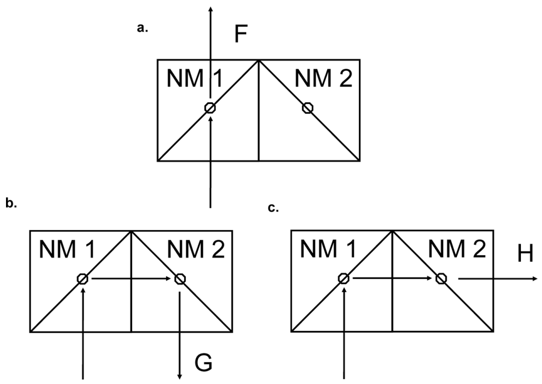

Figure 2. The optical router.

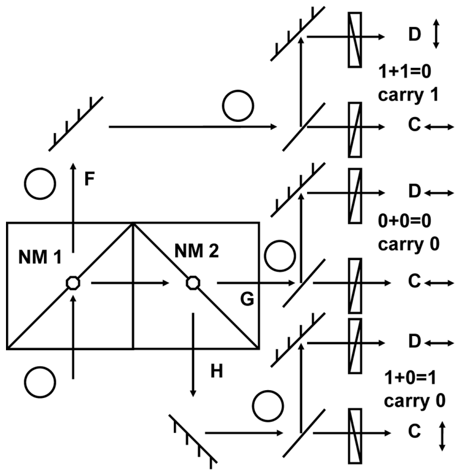

Figure 3. Adder without carry E.

in the optical switch 1, so do the vertical polarization light beams which act on the optical switch 2. Thus those nonlinear medium optical switches can be used to change the propagation direction of the probe beams to control the optical paths and realize the optical computing.

The procedure can be described like this: when both A and B are the horizontal polarization light beams, nonlinear effect will only happen in the optical switch 1, the circularly polarized light beams will propagate along the path F (figure 2a); when both A and B are the vertical polarization light beams, nonlinear effect will only take place in the optical switch 2, and the circularly polarized light beams will proceed along the path H (figure 2c); otherwise the circularly polarized light beams will transmit along the path G (figure 2b). The three different outputs are the results of these three different optical paths.

The calculational terminal is constituted by two parts: one is the 50 : 50 beam splitters (BSs), the other is the polarizers. When the circularly polarized light

Table 1. Truth table of the half adder.

A	B	C (Sum)	D (Carry)
$\leftrightarrow$	$\leftrightarrow$	$\leftrightarrow$	$\leftrightarrow$
$\leftrightarrow$	$\updownarrow$	$\updownarrow$	$\leftrightarrow$
$\updownarrow$	$\leftrightarrow$	$\updownarrow$	$\leftrightarrow$
$\updownarrow$	$\updownarrow$	$\leftrightarrow$	$\updownarrow$

beams cross a BS, they will be divided into two parts. These two beams will pass through two different polarizers independently. Each polarizer will change the circularly polarized light beam into a linear polarized light. The polarizers are fixed as in figure 3. Taking path H as an example, when the circularly polarized light beams transmit along path H, they will be divided into two circularly polarized light beams. In this case, the output beams will be vertical polarized beams and horizontal polarized beams after going through a vertical polarizer in terminal D and a horizontal polarizer in terminal C respectively.

The truth table of the half adder is shown in table 1.

4.2 *The designing of the full adder*

If a carry E is added to the adder considered in §3.1, it will become a full adder. The function of the carry E is as follows: when the carry is the horizontal polarization light beams, there is no impact on the results in table 1, and when the carry is the vertical polarization light beams, the results will be changed. So the whole system should be modified as in figure 4.

⋆ *The modification of controlling terminal*

In the full adder, as shown in figure 4a, there are three more equipments in the controlling terminal, i.e. one PBS and two BSs (one is 1 : 2, the other is 1 : 1). The added PBS will choose the optical paths according to the direction of the input polarization beams. If the input beams are in the horizontal direction, it will be out of use. Otherwise they will cross the two BSs. Those two BSs can split the input beams into three equal beams. Each will act on the corresponding nonlinear medium optical switch independently, then the optical switch will change the propagation direction of the polarized light beams.

⋆ *The modification of the calculational terminal*

After the carry E was introduced, the modification about the calculational terminal should be discussed as follows:

1. The initial sum output beams are the horizontal polarization light beams ($C = 0$).

In this situation, when the introduced carry E is the vertical polarization light beams, the sum output beams will be the vertical polarization light beams. So we should introduce another nonlinear medium optical switch as in figure 5. When the carry E is the vertical polarization light beams, the circularly polarized light beams will turn to another path, then the output C will be the vertical polarization light

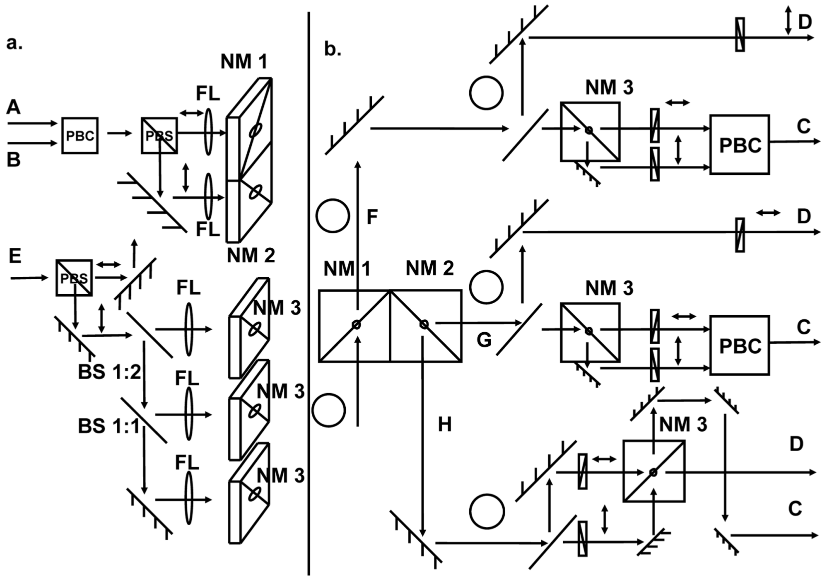

Figure 4. The whole computing scheme. (**a**) The scheme of the adapted controlling terminal. (**b**) The scheme of the adapted output terminal.

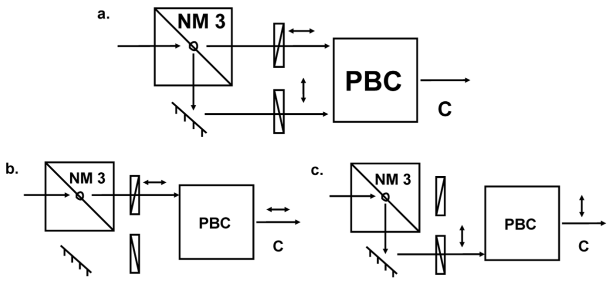

Figure 5. The modified proposal for former output C = 0.

beams (figure 5c). Otherwise the circularly polarized light will transmit along the former path (figure 5b).

2. The initial sum output beam is the vertical polarization light beams (C = 1)

In this condition, when the introduced carry is the vertical polarization light beam (E = 1), the sum output beams and the carry output beams will exchange with each other. So the scheme should be adapted as in figure 6a – introducing another nonlinear medium optical switch. If the carry E = 0, the polarized light beams will cross nonlinear medium optical switch and propagate along the former path (figure 6b). Otherwise the two polarized light beams will swap the optical paths with each other as shown in figure 6c.

The truth table for the full adder is given in table 2.

Table 2. Truth table of the full adder.

A	B	E	C (Sum)	D (Carry)
$\leftrightarrow$	$\leftrightarrow$	$\leftrightarrow$	$\leftrightarrow$	$\leftrightarrow$
$\leftrightarrow$	$\updownarrow$	$\leftrightarrow$	$\updownarrow$	$\leftrightarrow$
$\updownarrow$	$\leftrightarrow$	$\leftrightarrow$	$\updownarrow$	$\leftrightarrow$
$\updownarrow$	$\updownarrow$	$\leftrightarrow$	$\leftrightarrow$	$\updownarrow$
$\leftrightarrow$	$\leftrightarrow$	$\updownarrow$	$\updownarrow$	$\leftrightarrow$
$\updownarrow$	$\leftrightarrow$	$\updownarrow$	$\leftrightarrow$	$\updownarrow$
$\leftrightarrow$	$\updownarrow$	$\updownarrow$	$\leftrightarrow$	$\updownarrow$
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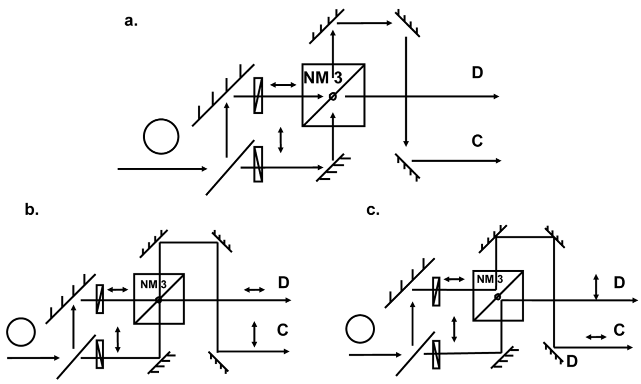

Figure 6. The modified proposal for former output C = 1.

5. Conclusion

In this paper, we give a scheme to realize all-optical half adder and full adder using the nonlinear medium optical switches. The all-optical computing system described above has several advantages: Firstly, it is easy to be integrated with appropriate fibres and optical switches. Secondly, all the numbers can be expressed by light beams. Finally, it is not a decimal system but a binary system. There are also some shortages. For instance, although the optical switches have been realized, the nonlinear effects are weak, the nonlinear liquid should convert into gas. Therefore, one has to explore which is the best nonlinear liquid medium. Moreover, how to quickly detect the polarization direction of the output beams is also difficult. In addition, comparing with quantum computation, the polarization coding rate limits the computation speed of the entire system. As a result, this scheme should be explored further before any demonstration can possibly occur. However, it may give a general idea as to how to realize the optical computing by optical switches.

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