An all-optical comparison scheme between two multi-bit data with optical nonlinear material

Kuladeep Roy Chowdhury, Abhijit Sinha, and Sourangshu Mukhopadhyay

Department of Physics, University of Burdwan, Golapbag, Burdwan-713104, India

Received February 18, 2008

Over the last few decades, several all-optical circuits have been proposed to meet the need of high-speed data processing. In some information processing architectures, the role of various analog and digital data comparisons is very important. In this letter, we proposed a multi-bit data comparison scheme. The scheme is based on the switching property of optical nonlinear material. Ultrafast operational speed larger than gigahertz can be expected from this all-optical scheme.

OCIS codes: 190.0190, 200.0200, 200.1130, 200.3760.
doi: 10.3788/COL20080609.0693.

The importance of optics has been recognized in the last three to four decades when high-speed logic operations were found to meet the basic requirements in data processing circuits[1,2]. Optics can be successfully implemented in different applications like arithmetic data processing, holographic memory, optical pattern recognition, and digital memory operations due to its inherent parallelism[3−5]. Within the optical domain, one may expect high-speed logic operation (∼THz) that would not be expected by electronic switching devices.

Optical nonlinear materials play an important role in optical computation, data processing and photonic switching. Optical nonlinear material can interact with light and sometimes change the colour of light from infrared region to visible colour spectrum. The refractive index of some optical nonlinear material largely depends on the intensity of the applied light, which has a significant application in optical soliton propagation, optical switching devices as well as memory schemes[6,7].

The refractive index for some specific types of isotropic optical nonlinear materials can be written as

$$n_{\mathrm{NL}} = n_0 + n_2 I, \tag{1}$$

where n_0 is a constant term, n_2 is the nonlinear correction term, I is the intensity of the light passing through the material. In case of CS_2 material, the values of n_0 and n_2 are 1.62 and 2.2×10^{-20} m^2/W respectively at 800 nm. For silica glass, the measured values of n_0 and n_2 are 1.46 and $(3.0 \pm 0.5) \times 10^{-20}$ m^2/W at 800 nm. Recent researches establish that the materials like polydiacetylenes, photo-thermo-refractive (PTR) glass, and chalcogenide glass have good nonlinearity[8−11]. Polydiacetylenes may show very fast response time (picoseconds response), which is hundred times greater than the fastest electronic switching. PTR glass can produce high nonlinearities and also can tolerate at least 100 kW/cm^2 of continuous-wave (CW) exposure by Yb fiber laser at 1085 nm. The values of n_0 and n_2 for PTR glass are measured to be 1.496 and 3.3×10^{-20} m^2/W at 800 nm. Two types of PTR glass (Virgin PTRG and Processed PTRG) are found to be most effective for nonlinear optical devices, both of which show large optical nonlinearities at 800 nm. Moreover, n_2 of PTR glasses does not vary after UV exposure as well as in thermal development. Practically, they can tolerate up to 400 °C. Their spectral and angular selectivities are below 1 nm and 1 mrad. With proper configuration, i.e., proper laser source and suitable optical nonlinear material, about 1 − 10 Tb/s operational speed can be expected. However, real-time operation can also be expected if we consider the size of the optical nonlinear material and the size of the beam splitter with smaller dimension.

The basic switching operation of an optical nonlinear material is shown in Fig. 1. X and Y are two input laser sources with equal intensities (I). In presence of anyone input, one may receive output at S end. When both input beams are present, output beam follows OT direction because of the high refractive index due to the high intensity ($2I$) of the light through the nonlinear material. A Nd:YAG laser with 1064-nm radiation is ideal for switching operation of optical nonlinear material. The dimension of the nonlinear block may be in the size of $500 \times 200 \times 200$ (nm), which is suitable for 100-mJ pulses. It has been seen that optical nonlinear materials which have self-focusing characteristic can easily be implemented in nonlinear optical devices. In such material, focusing length (L) largely depends on the power (P) and cross section (a) of the laser beam:

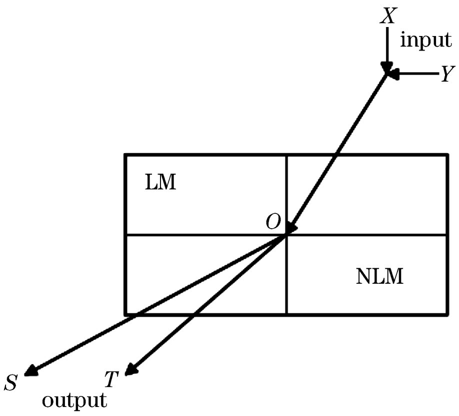

Fig. 1. Optical nonlinear material.

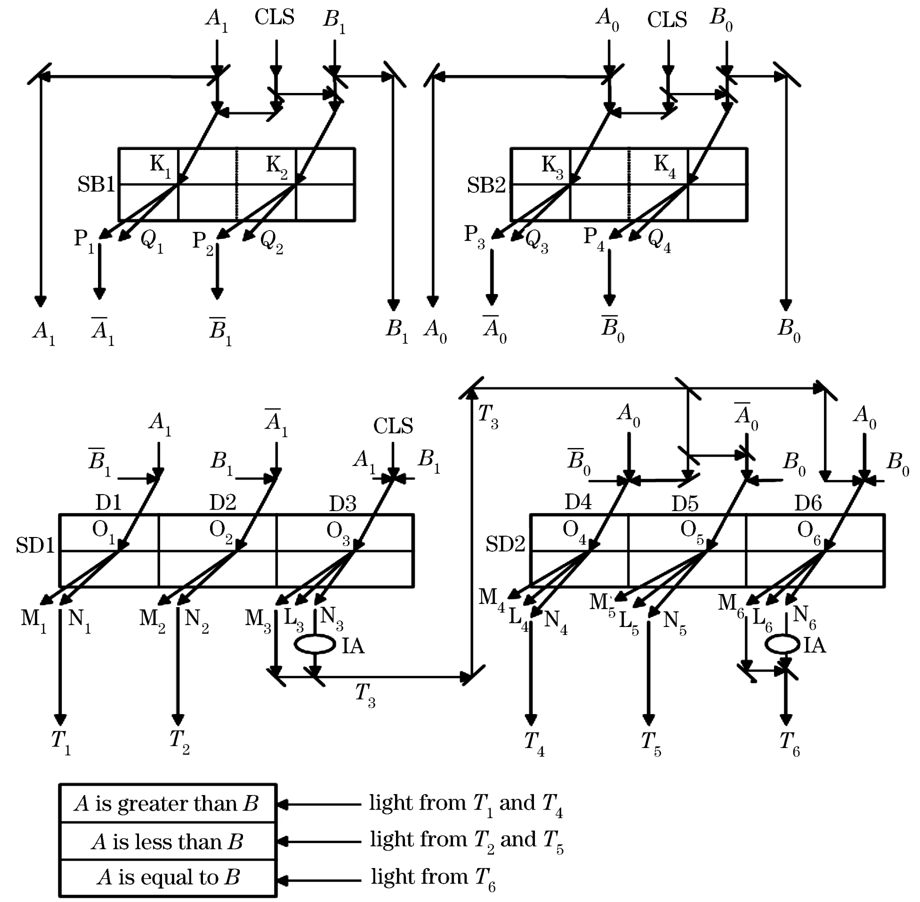

Fig. 2. All-optical multi-bit data comparison scheme.

$$P = \frac{\pi\varepsilon_0 n_0 c a^4}{8 n_2 L^2}, \tag{2}$$

where ε_0 and c are the free space permittivity and the free space velocity of light, respectively. Therefore, L can easily be smaller by increasing the power of the input radiation and reducing the cross section of the applied light.

The angle between S and T in Fig. 1 depends on the intensity and the nature of the incident laser beam and the used material. Normally, a beam with the diameter of 6 nm (point focused) and linewidth of 1.0 cm^{-1} has angular separation of $0.5 - 0.7$ mrad. Therefore small and integrated laser radiation detectors can easily separate and detect the output beams. Using the switching property in optical nonlinear materials, different logic gates can be formed and therefore different all-optical schemes can be developed[12−14].

Data comparison is an essential task in data processing circuits[15,16]. We proposed a multi-bit data comparison scheme based on bit-wise comparison technique from Most Significant Bit (MSB) to Least Significant Bit (LSB). The scheme develops the comparison mechanism in parallel between the two data. It can judge whether the two data are equal or unequal, i.e., one data is greater or less than the other.

In this scheme, two 2-bit numbers A_1A_0 and B_1B_0 are compared with each other. We first examine the MSBs A_1 and B_1. If A_1 is greater than B_1, for example, when $A_1A_0 = 10$ and $B_1B_0 = 01$, the number A_1A_0 would definitely be greater than B_1B_0. In the case of A_1 equals to B_1, we have to compare the next bit A_0 with B_0. If B_0 is found to be greater than A_0, for example $A_1A_0 = 10$ and $B_1B_0 = 11$, then B_1B_0 is greater than A_1A_0. For higher bits, we have to proceed in the same way.

The all-optical multi-bit data comparison scheme is shown in Fig. 2. A_1A_0 and B_1B_0 are the two input binary numbers appearing at the input of the scheme. In the all-optical circuit, the presence of light is denoted by binary number 1 and the absence by 0. SB1 is a block (combination of linear and nonlinear material), which consists of two NOT sub-blocks. A_1 and B_1 are two most significant bits, appearing at K_1 and K_2 points of the SB1 block along with a constant light source (CLS). Output follows K_1Q_1 direction in presence of light from A_1. When light from A_1 is absent, one may receive output at P_1 terminal. Output taken from P_1 end is denoted by $\overline{A_1}$. Similarly, output may be seen along K_2Q_2 direction in the presence of light from B_1 input. Output received from P_2 end can be represented as $\overline{B_1}$.

SB2 is another block (combination of linear and nonlinear material), which has also two NOT sub-blocks. A_0 and B_0 are taken as the inputs of SB2 block. Output is taken from P_3 and P_4 points in order to satisfy the NOT logic operation. Output taken from P_3 and P_4 points, can be represented as $\overline{A_0}$ and $\overline{B_0}$. Basically, $\overline{A_0}$,

$\overline{B_0}$, $\overline{A_1}$, and $\overline{B_1}$ are the NOT represented bits of A_0, B_0, A_1, and B_1 respectively. Next, SD1 block receives input at three different sections. Lights from A_1 and $\overline{B_1}$ (each having intensity I) are directed to appear at D_1. Output (intensity $2I$) would traverse $\mathrm{O}_1\mathrm{N}_1$ direction in presence of two input beams, both A_1 and $\overline{B_1}$. Presence of anyone beam, either A_1 or $\overline{B_1}$, leads the output (intensity I) to pass through $\mathrm{O}_1\mathrm{M}_1$ direction. To satisfy the AND logic operations, one may receive output from N_1 end. Therefore, the logic operation of the output taken from N_1 point can be represented as $T_1 = A_1\overline{B_1}$. In another section, i.e., in D_2, the block receives input light signal $\overline{A_1}$ and B_1 (each having intensity I). Presence of both inputs would direct the output beam (intensity $2I$) to follow $\mathrm{O}_2\mathrm{N}_2$ channel whereas any one input ($\overline{A_1}$ or B_1) may lead the output beam (intensity I) to pass through $\mathrm{O}_2\mathrm{M}_2$ direction. We wish to receive light from N_2 point. As a result, output satisfies the logic operation $T_2 = \overline{A_1}B_1$. In the D_3 section of the SD1 block, the inputs A_1 and B_1 appear along with a CLS with intensity of $3I$. When both input is present, output will travel along $\mathrm{O}_3\mathrm{N}_3$ direction with intensity $5I$. Again, no light in inputs A_1 and B_1 leads output to pass through $\mathrm{O}_3\mathrm{M}_3$ direction with the intensity $3I$. An intensity absorber (I.A.) has to be placed to reduce the intensity from $5I$ to $3I$ when output is taken from N_3 end. Output is to be taken from both M_3 and N_3 end jointly. Therefore, when both inputs A_1 and B_1 are present or absent, we will receive output T_3 with intensity $3I$. T_3 moves to the next nonlinear block SD2. In first section (i.e., in D_4), the inputs are A_0 (intensity I at 1 stage) and $\overline{B_0}$ (intensity I at 1 stage) along with T_3 (intensity $3I$ at 1 stage) taken from block SD1. When both inputs are present with T_3, output with intensity $5I$ will follow $\mathrm{O}_4\mathrm{N}_4$ direction. In absence of T_3, output will not travel in $\mathrm{O}_4\mathrm{N}_4$ direction. The ultimate output is taken from $\mathrm{O}_4\mathrm{N}_4$ direction and is denoted by T_4. In next section D_5, the inputs $\overline{A_0}$ and B_0 (both having intensities I at 1 stage) appear along with T_3 (intensity $3I$ at 1 stage). By similar application, output with intensity $5I$ will travel $\mathrm{O}_5\mathrm{N}_5$ direction in presence of lights from inputs $\overline{A_0}$ and B_0 and also light from T_3. In absence of light from T_3 or anyone input (either $\overline{A_0}$ or B_0), light will follow the other direction. Output received from $\mathrm{O}_5\mathrm{N}_5$ direction, is denoted by T_5. In last section D_6, the inputs are A_0 and B_0 (each having intensity I at 1 stage). The inputs appear at O_6 point accompanied with the light from T_3 (intensity $3I$ at 1 stage). When both inputs are present with T_3, output with intensity $5I$ follows $\mathrm{O}_6\mathrm{N}_6$ direction. Again the absence of both the input leads output with intensity $3I$ to pass through $\mathrm{O}_6\mathrm{M}_6$ direction due to the presence of light only from T_3. Output is taken from both M_6 end (intensity $3I$) and N_6 end (intensity $5I$) jointly. An intensity absorber or controller has to be placed in the ray direction from N_6 to reduce the beam intensity from $5I$ to $3I$. Output taken from M_6 and N_6 ends is denoted by T_6.

If light is found in either T_1 or T_4 channel, we can conclude that A is greater than B. The presence of light in T_2 or T_5 channel indicates that A is less than B. The appearance of light in T_6 channel will represent that A is equal to B.

We take $A = A_1A_0 = 10$ and $B = B_1B_0 = 11$ as example, i.e., $A_1 = 1$, $A_0 = 0$, $B_1 = 1$ and $B_0 = 1$. First, $A_1(= 1)$ and $B_1(= 1)$ appear at the input of the SB1 block. The output can be written as $\overline{A_1} = 0$ and $\overline{B_1} = 0$. At the same time, $A_0(= 0)$ and $B_0(= 1)$ are taken as inputs of the SB2 block. The outputs are $\overline{A_0} = 1$ and $\overline{B_0} = 0$. Next SD1 block receives inputs from $A_1(= 1)$ and $\overline{B_1}(= 0)$ at D1 section. Output follows $\mathrm{O}_1\mathrm{M}_1$ direction. Therefore, $T_1 = 0$. In D2 section, $\overline{A_1}(= 0)$ and $B_1(= 1)$ are taken as inputs. Output will traverse $\mathrm{O}_2\mathrm{M}_2$ direction, which gives $T_2 = 0$. At the same time $A_1(= 1)$ and $B_1(= 1)$ appear at the input in D3 section along with the CLS. In this case, output will follow $\mathrm{O}_3\mathrm{N}_3$ direction due to high intensity of light ($5I$). An intensity absorber is placed here to reduce the intensity from $5I$ to $3I$. Therefore, $T_3 = 1$. Light from D3 section (light from T_3 with intensity $3I$), activates SD2 block, i.e., presence of light in T_3 will direct the output in other channels.

SD2 block receives inputs $A_0(= 0)$ and $\overline{B_0}(= 0)$ in D4 section. In presence of light only in T_3 channel (intensity $3I$), output will traverse $\mathrm{O}_4\mathrm{M}_4$ direction (intensity $3I$). It is not our desired direction, therefore, $T_4 = 0$. At the same time, $\overline{A_0}(= 1)$ and $B_0(= 1)$ appear at D5 section with light from T_3 channel. In this case, we will receive light in our desired direction, i.e., $\mathrm{O}_5\mathrm{N}_5$ direction (intensity $5I$). Hence, $T_5 = 1$. In D6 section, the inputs are $A_0(= 0)$ and $B_0(= 1)$ accompanied with light from T_3. The output follows $\mathrm{O}_6\mathrm{L}_6$ direction (intensity $4I$). Since, our scheme is designed to receive light from M_6 and N_6 end only, we will get no light in T_6. Light appearing in T_5 channel indicates that $A(= 10)$ less than $B(= 11)$.

It is interesting to note that the scheme is based on bitwise comparison technique. No subtraction is required to compare the data. So the scheme is not very complicated. We have shown here the process of comparison of the magnitude of data, not its sign. Sometimes, it is necessary to include the comparison of signed bit data. Our future task will include the development of comparison operation between two signed bit data. One can extend the present scheme for comparison of some higher order multi-bit data. In that case, we have to use more nonlinear switches in parallel. The proposed scheme may suffer $0.1 - 0.2$ dB/m attenuation loss if we consider silica as nonlinear medium. As our scheme is in the order of few micrometer, the loss is negligible. Moreover, the attenuation loss may be reduced to 0.001 dB/m if we consider slow light applications at 1.56-μm wavelength. Besides, splitting loss can be easily overcome with the use of 'no loss' splitters and monolithic laser devices that utilize external or internal mirrors.

The whole operation shown here is parallel. Several inputs can be accommodated due to inherent parallelism in optics. Moreover, such all-optical circuits require very small power in order of 10^{-6} W, which is very small compared with equivalent electronic circuit. By proper accommodation of optical nonlinear material, the scheme can be extended for comparison of data having higher bits. It is also important that all sources should have the same intensity at 1 stage. They should be coherent, otherwise the system may not work as expected.

K. R. Chowdhury's e-mail address is r_kuladeep@rediffmail.com.

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