論文 89-26-10-13

Real-time Optical Logic Processors by Two-Wave Mixing in $BaTiO_3$ Crystal

($BaTiO_3$ 결정에서의 두 광파 혼합현상을 이용한 광 논리처리기)

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要 約

광굴절 매질 내에서 입력빔 강도에 따른 비선형 광파 결합현상을 해석하였다. 신호빔 포화현상, 펌프빔 공핍 현상은 입력광 강도의 함수로서 결정되어지며, $BaTiO_3$광굴절 매질 내에서 이들 현상을 이용한 광논리 처리기를 구현하고 실험하였다.

Abstract

Nonlinear beam coupling phenomena in photorefractive materials are analyzed as a function of the input beam intensities. Signal beam saturation and pump beam depletion are shown to be the intensity-dpendent functions of these materials. Utilizing these phenomena in a photorefractive $BaTiO_3$ crystal, optical logic processors such as AND, OR, NOT, etc., are implemented.

I. Introduction

Optical processing technique offers both the high speed and parallelism required for digital signal processing and computation of high bandwidth signal such as 2-D or 3-D images[1],[2].

Nonlinear optical devices based on the liquid crystal light valve, Fabry-Perot resonator, acoustooptic devices, and recently, four-wave mixing in photorefractive materials have been reported for parallel optical signal processor[3].

But in four-wave mixing geometry, processing must be done in quasi real-time mode because the recorded information has to be retrived by another reading beam[4],[5].

In this paper, we report an implementation of real-time optical logic processors using a photorefractive $BaTiO_3$ crystal. For logic operations, two-beam coupling effects in a $BaTiO_3$ crystal are briefly reviewed, and then signal beam saturation and pump beam depletion phenomena

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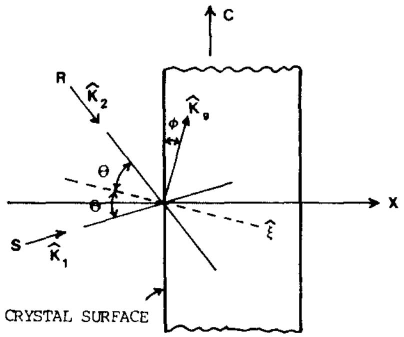
接受日字 : 1989年 6月 21日
(※ 본 연구는 한국전자통신연구소의 연구비 지원으로 이루어졌읍니다.)

according to the two input beam intensity ratio are analyzed.

As applications of these phenomena, several optical logic operations of AND, OR, NOT, etc., are performed.

II. Two-Beam Coupling in Photorefractive BaTiO$_3$ Medium

Fig.1 shows a geometrical configuration of two-beam coupling in nonlinear photorefractive medium. In general, energy transfer between two incident beams in photorefractive media can be explained by the volume phase grating which is induced by the interference fringe pattern of the two beams.



Kg, grating vector: c, crystal c-axis; S, signal beam; R, reference beam

Fig.1. Geometrical configuration of two-wave mixing.

We let the two incident waves be

$$S(z,t)=[I_1(z,t)]^{\frac{1}{2}}\exp\{i[\omega t+\psi_1(z,t)]\} \quad (1)$$

$$R(z,t)=[I_2(z,t)]^{\frac{1}{2}}\exp\{i[\omega t+\psi_2(z,t)]\} \quad (2)$$

where $I_i(z,t)$ is the intensity of two incident waves, and $\psi_i(z,t)$ represents the phase of two beams.

Under the slowly varying envelope approximation and with negligible absorption, coupled wave equation can be derived as follows;

$$\frac{dI_1}{ds}=+\Gamma\frac{I_1I_2}{I_0} \quad (3)$$

$$\frac{dI_2}{ds}=-\Gamma\frac{I_1I_2}{I_0} \quad (4)$$

In above equations, I_O is the total intensity of two beams and Γ is the gain coefficient characterized by the coupling coefficient γ,i.e., $\Gamma = 2\mathrm{Re}(\gamma)$.

The solutions of Eq.(3),(4) are given by[3]

$$I_1(s)=\frac{I_0(0)}{1+(I_2(0)/I_1(0))e^{-\Gamma s}} \quad (5)$$

$$I_2(s)=\frac{I_0(0)}{1+(I_1(0)/I_2(0))e^{\Gamma s}} \quad (6)$$

where $I_1(0)$, $I_2(0)$ represent the intensities of two input waves.

We will define the gain for the i-th beam as

$$G_0=\frac{I_i(I_j\neq 0)}{I_i(I_j=0)} \quad (7)$$

Then the amplification factors of signal beam and pump beam are

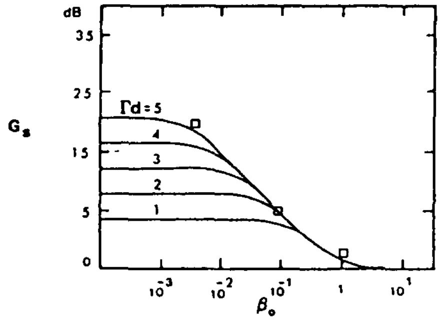
$$G_S=\frac{(1+\beta_0)e^{\Gamma d}}{1+\beta_0 e^{\Gamma d}} \quad (8)$$

$$G_P=\frac{(1+\beta_0)\ \exp(e^{\Gamma d})}{\beta_0+\exp(-\Gamma d)}=\frac{\beta_0+1}{1+\beta_0\exp(\Gamma d)} \quad (9)$$

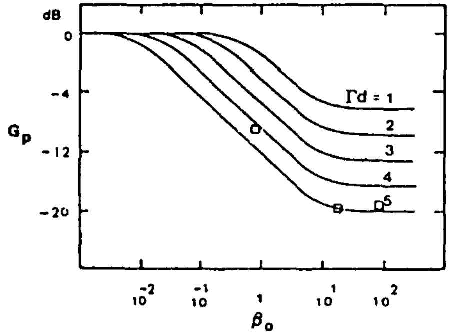
where the input signal beam to pump beam intensity ratio is $\beta_O=I_1(0)/I_2(0)$, and the d is the effective interaction length.

In Fig.2 (a), the gain characteristic of the signal beam described in Eq.(8) is plotted as a function of β_O. As shown in the Figure, signal beam saturation effects will occur below the critical value of β_O. For example, signal beam saturation occurs $\gamma_O < 10^{-3}$ for $\Gamma d=5$. This scheme can be applied to perform optical AND operation. The signal beam at the output will be amplified by a factor of saturation gain, exp (Γd), only when both A and B differ from zero. With the optimized gain coefficient, exp (Γd), is usually greater than the order of 10^3. The same operation can be applied to OR operation, too.

Also, the gain characteristic of the pump beam in Eq.(9) is plotted in Fig.2 (b). This shows



(a) Signal beam satuation region



(b) Pump beam depletion region

Fig.2. Plot of gain Gs and Gp with β_0. (□ : measured values)

that pump beam depletion effect will occur over the critical value. For example, pump beam depletion occurs $\beta_0 > 10^1$ for Γd=5. This phenomenon of pump depletion can be applied to perform the optical NOT operation. For the signal beams at a low-intensity level (logic 0), the pump beam at the output will be close to its input value $I_2(0)$. However, with the input signal at a high intensity level (logic 1), the resultant value of $\beta_0 \gg 1$ leads to depletion of the pump beam at the output (logic 0) according to Eq. (9). This pump depletion mode of operation can be applied to logic $\overline{A > B}$, and $\overline{B > A}$ operations. The truth table of above operations is shown in table 1.

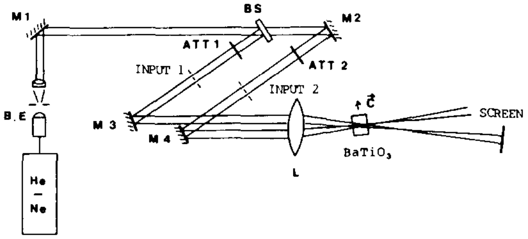
III. Experimental Result and Discussion

Table 1. Truth table of implemented logic operations.

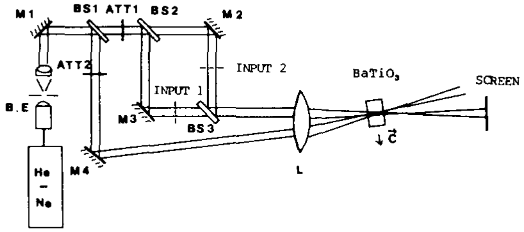
A	B	A+B	A · B	$\overline{A}$	$\overline{B}$	$\overline{A>B}$	$\overline{B>A}$
0	0	0	0	1	1	0	0
0	1	1	0	1	0	0	1
1	0	1	0	0	1	1	0
1	1	1	1	0	0	0	0

The optical logic operations described in the previous section have been experimentally verified. Optical AND, OR, NOT, $\overline{A > B}$, and $\overline{B > A}$ operations are performed employing systems schematically shown in Fig.3 (a), (b) and (c), respectively.

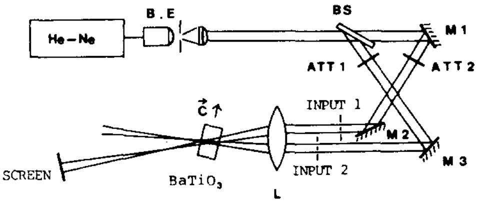
In all the experiments, a photorefractive $BaTiO_3$ crystal (7.56 x 5.12 x 5.48mm) with



(a) AND operation



(b) OR operation

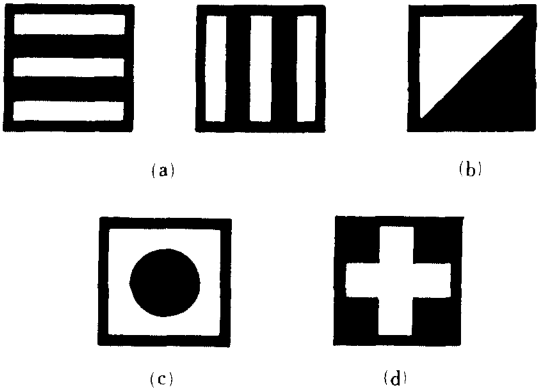


(c) NOT, $\overline{A > B}$, $\overline{B > A}$ operations

BS, beam splitter; M's, mirrors; L's, lens; ATT's, attenuator; B.E., beam expander.

Fig.3. Experimental setup for optical logic operations.

tetragonal symmetry structure (n_o=2.41, and n_e= 2.36) is used. The angle between two incident beams was $2\theta=8^\circ$, and the angle between the grating vector and crystal c-axis was measured 15° in the crystal. All the experiments were performed under the condition of exp (Γd) =151(with values of $\theta=4^\circ$, $\phi=15$, d=5.1/cos 15°=5.24 mm, Γ=0.95/mm, Γd= 5.02)


(a) (b)

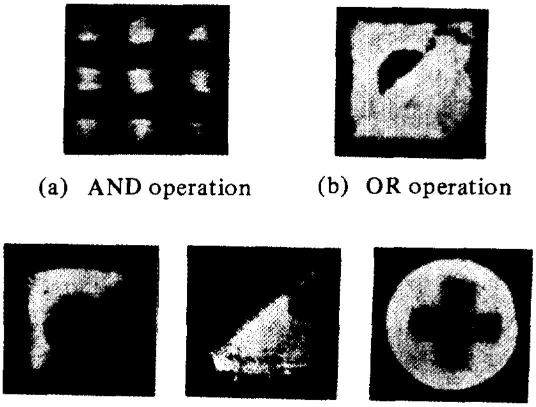
(c) (d)

Fig.4. Input masks used in experiments.

The four input masks as shown in Fig.4 (a) (b), (c), and (d) were used in all the experiments Fig. 5 (a) shows the result of AND operation of inputs shown in Fig.4 (a). Fig.5 (b), (c), and (d) represent OR, A > B, B > A operations, respectively, between Fig. 4 (b) and (c) images. Fig. 5 (e) is the result of NOT operation of Fig. 4 (d) image. AND, OR operations are performed in the signal saturation mode with β_o=1/300. NOT, $\overline{A > B}$, $\overline{B > A}$ operations are performed in the pump depletion mode with β_o=18. In the signal saturation mode, although the condition exp (Γd) $\ll$ 1 is not fully satisfied, we obtained relatively good result.

IV. Conclusions

We performed real-time optical AND, OR, NOT, and other logic operations utilizing signal beam saturation and pump beam depletion phenomena of two-beam coupling in a photorefractive $BaTiO_3$ crystal.


(a) AND operation (b) OR operation

(c) $\overline{A>B}$ (d) $\overline{B>A}$ (e) NOT operation

Fig.5. Experimental results of optical logic operations.

The results obtained from the above experiment can be easily applicable to the real-time image processor such as image subtraction and addition, and can provide a basic device for the future implementation of optical digital computing system.

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