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All-optical logic-gates based on bacteriorhodopsin film*

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Based on self-diffraction in bacteriorhodopsin (bR) film, we propose all-optical NOT, XOR, half adder and XNOR logic operations. Using the relation between diffraction light and the polarization states of recording beams, we demonstrate NOT and XNOR logic operations. Studying the relation of polarization states among the diffracting, recording and reading beams, we implement XOR logic and half adder operations with three inputs. The methods are simple and practicable.

Keywords: all-optical logic-gates, self-diffraction, bR film, half adder
PACC: 4270G, 4225B, 4280V

1. Introduction

Bacteriorhodopsin (bR) film is one kind of excellent nonlinear optical material. It has many excellent properties,[1] such as high quantum efficiency that can reach 64%, good spatial resolution which is more than 5000line/mm, over 10^6 write–read–erase cycles, high thermal endurance up to 140°C, and a prolonged lifetime of M state for different applications.[2] Moreover, it has high stability under photo-degradation and elevated temperatures. Because of the many advantages of the bR film, it is very suitable for preparing optical devices. Since 1986, several logic operations have been demonstrated with photorefractive materials,[3−6] and many logic operations have been based on bR films,[7−12] such as all-optical logic operations utilizing the modulation property of bR films,[10] logic operations with polarization properties of degenerate four-wave mixing (DFWM),[13,14] the logic operation using the most stable two states in bR,[7] and the all-optical switches made from bR films.[15] In recent years, more and more researchers have paid attention to the study of optical logic devices.[16] Kim demonstrated an all-optical half adder using semiconductor optical amplifier devices,[17] and full adders have been demonstrated by other methods.[18−21] In a binary system, all the logic operations are based on digital adders without carry, which are called half adders. An all-optical half adder is a basic unit to operate in optical binary systems. We proposed and demonstrated all-optical logic gates by self-diffraction in a bR film. Since the experiment can be demonstrated by a single light source, this method makes the experiment simpler than that by the phase conjugation in DFWM. Based on the relation of polarization states among recording, reading and diffracting beams, we design a XOR logic operation (or a half adder with two inputs) and a half adder with three inputs.

2. Holograph grating

bR is a light-transducing protein in the purple membrane of Halobacterium halobium,[22,23] one of the oldest organisms on the Earth. It populated the

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salt marshes during the Archaean era more than one billion years ago, and its "purple membrane" continues to surprise us as a kind of new and dramatically nonlinear optical material which has many applications in photonics. bR is extremely sensitive to light in a broad visible region. On absorbing photons, bR undergoes a complex photocycle characterized by several spetroscopically distinct thermal intermediates, among which there are two main states: one is the ground state (B state), another is the longest-lived state (M state). Under the light illumination there are always some molecules in the intermediates, and the absorption coefficient and refractive index of these intermediates are different from those of the ground state. Thus, the absorption coefficient and refractive index of a bR film are dependent on the wavelength and intensity of the incident light.[24] With different wavelengths of light illuminating on the bR film, the relationship among the light-induced changes of the absorption coefficient, refractive index and intensity are quite different. The absorption peaks in the visible range are located at wavelengths of 568 and 412nm. When the yellow light illuminates the bR film, the molecules in the B state decrease while those in the M state increase. The higher the incident yellow intensity, the more molecules the M state contains. When the blue light illuminates the bR film, the number of molecules in the M state decreases and that in the B state increases. The higher the incident blue intensity, the fewer the molecules in the M state. Based on the relation between the refractive index change, incident wavelength and illumination intensity, when the bR film is illuminated by a red light (632.8nm), which is near 568nm compared with 412nm, the bR molecules in the M state increase, and the reflective index change increases with increasing incident intensity and finally reaches saturation.

When two laser beams with the same wavelength (632.8nm) and the same polarization direction illuminate the bR film, they interfere in the bR film and create interference fringes, whose intensity is sinusoidally modulated in spatial distribution. Compared with the change of refractive index, the change of absorption coefficient is very small for the red light (632.8nm), and the grating formed is mainly phase grating because of the large change of refractive index.

Due to the photo-induced anisotropy in the bR film, absorption coefficient and refractive index are changed by compounding beams with the same wavelength but perpendicular polarization directions, and a holograph grating is recorded in the bR film. This is called a polarized holograph, which is widely used for image processing and all-optical logic gates.[1,8,13,14] According to the property of the dichroism and birefringence in the bR film, the polarized holograph includes both the absorption and phase holographs, and the phase grating is dominant.

3. Experimental setup

Suppose that the recording beams are $\boldsymbol{R}$ and $\boldsymbol{S}$ with the same wavelength and intensity, and both are linearly polarized. Whether the polarization directions of $\boldsymbol{R}$ and $\boldsymbol{S}$ beams are the same or perpendicular, a grating can be formed and the two beams are diffracted by the grating consisting of these beams. This kind of diffraction is called self-diffraction.[25,26] As long as the angle between $\boldsymbol{R}$ and $\boldsymbol{S}$ is favourable, self-diffraction occurs.

The experimental setup is shown in Fig.1. To obtain high diffraction efficiency, a He–Ne laser beam (632.8nm) is divided into two by a beam splitter, and the two beams (recording beams) are incident on the bR film at an angle 2°. The two attenuators (A) make the two incident beams have the same intensity of 0.20mW/cm^2. When the angle between $\boldsymbol{R}$ and $\boldsymbol{S}$ is less than 6°, self-diffraction can be observed. In order to obtain a polarized hologram, a half wavelength plate (HP) is inserted into a branch. The experimental results are shown in Table 1(a) where V denotes vertical polarization and H denotes horizontal polarization.

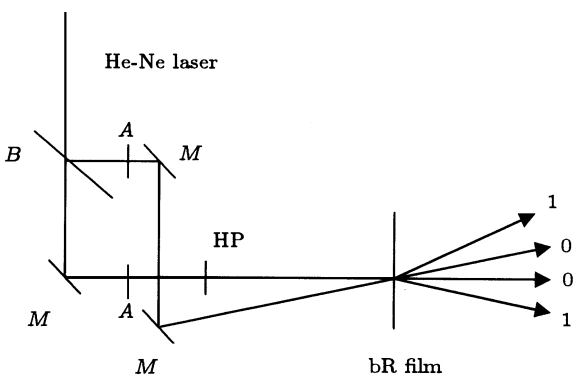


Fig.1. Experimental setup for self-diffraction (B: beam splitter, M: mirror, HP: half wavelength plate, A: attenuator).

4. Logic gates and half adder

4.1. XNOR operation

From Table 1(a), we define the vertical polarization (V) and horizontal polarization (H) as logic 0 and 1, the recording beams of $\boldsymbol{R}$ and $\boldsymbol{S}$ as logic inputs of A and B respectively, and the diffracted intensity as logic output C. When $\boldsymbol{R}$ and $\boldsymbol{S}$ are of the same polarization, output C is defined as logic 1; in contrast, when $\boldsymbol{R}$ and $\boldsymbol{S}$ are perpendicular polarization to each other, C is defined as logic 0. From Table 1(a), logic 1 corresponds to the diffraction intensity 0.43–0.60μW/cm^2; and logic 0 corresponds to the diffraction intensity 0.23μW/cm^2. In order to keep the logic function reliable, the diffraction intensity of more than 0.38μW/cm^2 is defined as logic 1, while the diffraction intensity of less than 0.28μW/cm^2 as logic 0. Therefore, Table 1(a) can be changed into Table 1(b) which shows the function of logic XNOR.

Table 1. (a) The relation between polarization states of recording beams and diffraction intensity.

Recording R Polarization states	V	V	H	H
Recording S Polarization states	V	H	V	H
Diffraction intensity/μW/cm^2	0.60	0.23	0.23	0.43

Table 1. (b) XNOR logic operation.

input		output
A	B	C
0	0	1
0	1	0
1	0	0
1	1	1

4.2. NOT operation

Figure 2 is the schematic diagram of the polarization relation between recording and diffraction beams. The polarization of self-diffraction beam $\boldsymbol{R}_1$ is perpendicular to that of the recording beam $\boldsymbol{R}$, while the polarization of self-diffraction beam $\boldsymbol{S}_1$ is perpendicular to that of the recording beam $\boldsymbol{S}$. Table 2(a) shows the polarization states of the beams $\boldsymbol{R}$, $\boldsymbol{S}$, $\boldsymbol{R}_1$ and $\boldsymbol{S}_1$. In Table 2(a), if the vertical polarization (V) and horizontal polarization (H) are defined as logics 0 and 1, respectively, and the recording beam $\boldsymbol{R}$ and the corresponding diffraction beam $\boldsymbol{R}_1$ are defined as logics input A and output C respectively, we can obtain Table 2(b) which shows the function of logic NOT.

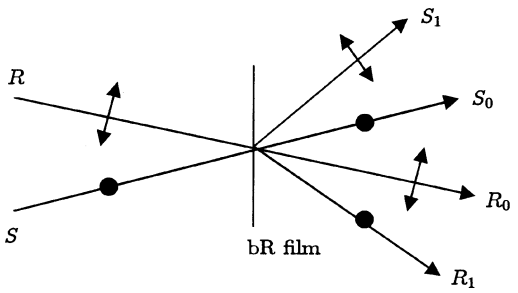


Fig.2. Schematic diagram for the measured polarization relations between recording and diffraction beams.

Table 2. (a) The relations of polarization states between recording and the diffraction beams.

		Polarization states	
Recording beam	$\boldsymbol{R}$	V	H
	$\boldsymbol{S}$	H	V
Diffraction beam $\boldsymbol{R}_1$		H	V
Diffraction beam $\boldsymbol{S}_1$		V	H

Table 2. (b) NOT logic operation.

input	output
A	C
0	1
1	0

4.3. Half adder operation

On Fig.1, a reading beam $\boldsymbol{T}$ is added as the bisector of the angle between the recording beams $\boldsymbol{R}$ and $\boldsymbol{S}$, which is equal to 1°. On the one hand, the beam $\boldsymbol{T}$ reads the grating induced by $\boldsymbol{R}$ and $\boldsymbol{S}$ beams, and on the other hand it induces self-diffractions with $\boldsymbol{R}$ and $\boldsymbol{S}$ respectively (see Fig.3). The intensity of the reading beam is 0.18mW/cm^2 and that of the each recording beam is 0.20mW/cm^2. When the normal and polarized holograms are recorded, the first-order diffraction beam $\boldsymbol{R}_1$ principally includes two parts, one is the self-diffraction beam induced by the $\boldsymbol{R}$ and $\boldsymbol{S}$ beams, and the other is the diffraction beam from the beam $\boldsymbol{T}$ that reads the grating induced by the $\boldsymbol{R}$ and $\boldsymbol{S}$ beams. A polarization plate $\boldsymbol{P}$ is inserted into the diffraction beam $\boldsymbol{R}_1$ to measure the pure polarization signal, and the polarization directions of the reading, recording and diffracting beams are measured. The polarization direction of the diffraction beam depends on the polarization directions of the reading beam and the two recording beams.

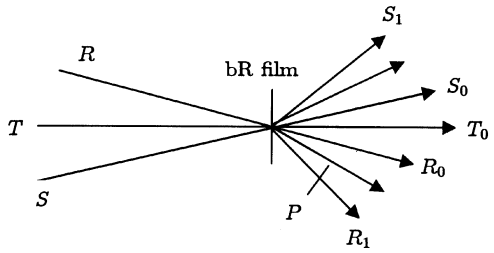


Fig.3. Schematic diagram for half adders.

Table 3(a) shows the experimental results. When the recording beams with the same polarization direction, a normal hologram is recorded in the bR film, and the polarization direction of the diffraction beam is the same as that of the reading beam. When recording beams are polarized perpendicularly to each other, polarized hologram is recorded, and the polarization direction of the diffraction beam $\boldsymbol{R}_1$ is perpendicular to that of the reading beam.

Table 3. (a) The relations of polarization states among recording beams of $\boldsymbol{R}$ and $\boldsymbol{S}$, the reading beam of $\boldsymbol{T}$, and the diffraction beam of R_1.

		Polarization states							
Recording beam	$\boldsymbol{R}$	V	V	V	V	H	H	H	H
	$\boldsymbol{S}$	V	V	H	H	H	H	V	V
Reading beam $\boldsymbol{T}$		V	H	V	H	H	V	H	V
Diffraction beam $\boldsymbol{R}_1$		V	H	H	V	H	V	V	H

Table 3. (b) Logic states corresponding to Table 3(a), 0 and 1 represent the vertical and horizontal polarizations, respectively.

		logic states							
Recording beams	$\boldsymbol{R}$	0	0	0	0	1	1	1	1
	$\boldsymbol{S}$	0	0	1	1	1	1	0	0
Reading beam $\boldsymbol{T}$		0	1	0	1	1	0	1	0
Diffraction beam $\boldsymbol{R}_1$		0	1	1	0	1	0	0	1

Table 3. (c) Half adder logic operation.

input			output
A_1	A_2	A_3	C
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	1	1	1
1	1	0	0
1	0	1	0
1	0	0	1

Table 3. (d) XNOR logic operation.

input		output
A	B	C
0	0	0
0	1	1
1	0	1
1	1	0

When the vertical polarization (V) is defined as logic 0 and horizontal polarization (H) as logic 1, Table 3(a) can be replaced by Table 3(b). In Table 3(b), two recording beams and one reading beam are used as the input beams (A_1, A_2 and A_3), and the diffraction beam as the output beam (C) of the half adder, and we implement the operation of half adder with the three inputs. The logic relation between the inputs and the output is shown in Table 3(c).

4.4. XOR operation

In Table 3(a), supposing the recording beam $\boldsymbol{R}$ is vertical polarized, the polarization direction of the recording beam $\boldsymbol{S}$ and reading beam $\boldsymbol{T}$ are defined as the logic inputs A and B, respectively, and the polarization direction of the diffraction beam $\boldsymbol{R}_1$ is defined as logic output C, thus we have the operation of logic XOR. It is also a half adder with the two logic inputs. The logic relation is shown in Table 3(d).

5. Conclusion

We have demonstrated a new way to implement optical Boolean logic operations and the half adder through the relation between the diffraction light and polarization states of the recording, reading and diffracting beams. The bR film is very stable,[1,19] and has many advantages. The lifetime of the M state is

a main factor that influences the delay time of logic gates. In our experiment, due to the longer lifetime of the M state, the delay time of logic gates is of the order of second. But the delay time can be controlled by adjusting the lifetime of the M state, for example, it can be shortened to the order of microsecond.[26] Moreover, the noise in the bR film is quite low, so it is possible to produce high quality logic devices.

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