

Magneto-Optical Waveguide Gates for Digital Logic Operations

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Abstract— Developed mechanisms for controlling magneto-optical qubits can be used for the various magneto-optical logic gates modeling in waveguide configuration, including implementation of the half-adder that performs parallel and simultaneous *AND* and *XOR* operations. The developed devices can be used to design a wide range of information processing and transmission devices based on new principles.

Keywords— optical waveguide, logic gate, magneto-optical half-adder, magneto-optical qubits, logic device.

I. INTRODUCTION

The obvious progress in the development of information technologies has led to the fact that cyberspace (or, as it is also called, the virtual world) is becoming an area where the most advanced achievements and approaches of modern science and technology intersect. For processing terabytes of information, it is no longer possible to use only conventional computers and supercomputers, so active research is being conducted in different countries of the world to create quantum computers and artificial intelligence systems based on the new principles.

Despite the fact that quantum information processing implies radical advantages in computer computing, communication security, and ultra-precise measurements compared to classical processing, the ways to create real-world devices are still at the search stage.

This article presents the results of research aimed at studying the possibilities of applying the properties of magneto-optical (MO) qubits in various fields of science and technology for designing a wide range of devices for processing, storing and transmitting information on new principles using the element base of logic gates with an alternative architecture.

II. RESULTS AND DISCUSSION

The concept of "magneto-optical qubits" is described in detail in [1]. Note that one of the main advantages of MO qubits over optical qubits is the ability to increase the coherence time of qubits by six or more orders. Due to this, it is possible to construct models of quantum information processing devices with minimal effort, starting from the simplest classical logic *AND*, *XOR* and *NOT* gates up to the quantum *C-NOT* (controlled-not) gate, including half-adders and adders, using the basic concepts of digital logic.

Digital logic (algebra of logic, Boolean algebra) operates only with two values of variables corresponding to binary possible numbers or logical values: 0 and 1. As a result, digital logic circuits can be analyzed and synthesized functionally using logic algebra, truth tables, and other tools that can

describe the relationship of zeros and ones in the scheme [2, 3].

A logical value of 0 or 1 is called a binary digit or bit. To set a variable with more than two values, use sets of n bits to represent 2^n different values. A logic circuit for which the values of output signals are uniquely determined by a combination of the values of its input signals at a given time is called a combinational circuit. It consists of digital circuits without storing data [3].

The operation performed by each such scheme can be fully described by a truth table that lists all combinations of input signals and their corresponding signal values at the outputs. It should be noted that a very useful theorem is proved in the algebra of logic: Any logical function can be represented by a super-position of three functions: logical addition or disjunction (*OR*), logical multiplication or conjunction (*AND*), and negation or inversion (*NOT*).

Thus, only three basic logic circuits that implement the *AND*, *OR* and *NOT* functions are sufficient to construct any combinational scheme. In Fig. 1 the above logic gates symbols and the corresponding truth tables are presented. Notation and truth tables for schemes *AND* and *OR* can be extended to any number of inputs. The functions implemented by circuits are defined as follows:

The *AND* element generates 1 at the output only if all its inputs contain 1. The logical function implemented by the *AND* has the form:

$$Y = X_1 \cdot X_2 \cdot \dots \cdot X_m. \quad (1)$$

The *OR* circuit generates 1 at the output only if 1 is presented at least in one of its inputs. A logical function implemented by the *OR* element has the form:

$$Y = X_1 + X_2 + \dots + X_m. \quad (2)$$

The *NO* circuit generates an output signal that is the opposite to the input signal. The logical function implemented by the *NOT* element has the form: $Y = \bar{X}$.

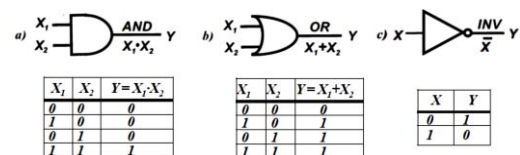


Fig. 1. Main logic elements and their truth tables: a) *AND*; b) *OR*; c) *NO*

The circle shown at the output of the inverter is an inversion symbol and is used in images of logic elements to indicate the inversion operation. Just as for schemes *AND* and *OR*, symbols and truth tables can be extended to any number of inputs for schemes *AND-NOT* and *OR-NOT*.

Let's consider an alternative possibility of building gates that are directly compatible with encoding and transmitting information in fiber-optic communication lines. Previously, it was reported that it is possible to use the magneto-optical (MO) Faraday effect for implementing various logic devices using waveguides made of organic compounds such as Plexiglas, which combine good transparency with a sufficiently large specific Faraday rotation [1, 4].

The classical half-adder consists of two inputs for signals X_1 and X_2 and two outputs: the sum channel Y_1 (*Sum*), and the carry channel Y_2 (*Carry*), shown in Fig. 2 with a truth table for the *Sum* and *Carry* channels.

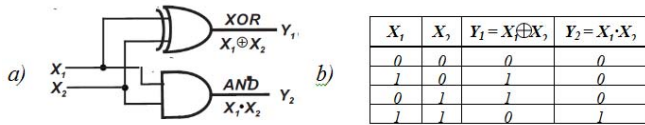


Fig. 2. a) Symbol of the half-adder, and b) the truth table.

Fig. 3 shows the optical scheme of the manufactured model of the simplest MO half-adder. The developed and experimentally tested magneto-optical half-adder for checking the functioning of logic gates based on the X -configuration of the waveguide made it possible to study in practice the main properties of the developed magneto-optical logic gates, such as those performing the *AND* and *XOR* operations.

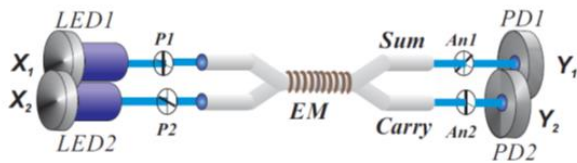


Fig. 3. Diagram of a magneto-optical half-adder (peripheral electronics are not shown): LED1 and LED2 are light-emitting diodes ($\lambda = 440 \text{ nm}$) for X_1 and X_2 signals with *HP* and *VP* orientations of light polarization, EM is an electro - magnet; Sum is the Sum waveguide channel; Carry is the transfer channel; An1 and An2 are analyzers; PD1 and PD2 are photodiodes for the Sum and Carry channels.

The main element that we used initially as a magneto-optical waveguide in our researches is a Plexiglas sample, carefully processed and polished to avoid optical losses on scattering and absorption. An electromagnet is a multi-layer coil of copper wire. The purpose and functions of the other parts are clear without further explanation.

Let the primary binary encoding of input signals be performed using pulse modulation, i.e., the LED is on – “1”, off – “0”.

Some additional explanations about the physical nature of the input and output signals should be provided. Information encoded in the form of electrical signals is converted into video pulses and fed to the LEDs, which convert them into optical radiation with pulses of a certain duration. Then these signals A and B pass through the polarizers and become linearly polarized, respectively, with mutually perpendicular *HP* (horizontal) and *VP* (vertical) polarizations.

Now we can denote them as a logical variables X_1 and X_2 , or as base vectors $|0\rangle$ and $|1\rangle$, orthogonal to each other, which fall on one or another input branch of the waveguide. [5]

$$X_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}; X_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (3)$$

A logic device with qubits can be described as a quantum register, which is more informative than a classical one. [6]

If an ordinary optical qubit is represented as a vector in Hilbert space with expansion, for example, in $|0\rangle$ and $|1\rangle$ (see above: (1)), then when it is placed in an alternating magnetic field, the spin degeneracy is removed and the vector describing the photon polarization properties begins to precess around to the initial equilibrium position with the frequency of the applied field. The maximum angle of the precession cone will be proportional to the angle of the Faraday rotation of the waveguide material.

It is convenient to describe these forced oscillations (Faraday rotation) with a new vector and measure its characteristics in the corresponding bases, selecting the orientation of the analyzer relative to the polarizer. It should be noted that for these new (magneto – optical) waves, the same quantum laws continue to work as for their progenitors – photons.

Under the influence of an alternating magnetic field due to the Faraday effect, the optical signal becomes magneto-optical. Thus, instead of purely optical X_1 and X_2 signals, it makes sense to consider magneto-optical signals x_1 and x_2 that occur when they fall into the region of a waveguide with an electromagnet coil (Faraday area: Fig. 4).

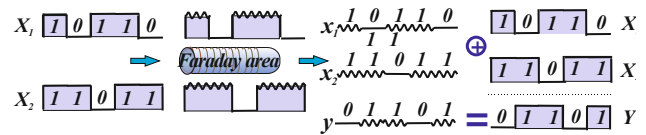


Fig. 4. Evolution of processed signals.

Under the influence of a magnetic field, optical signals passing through the analyzer with the desired orientation acquire an additional variable intensity component, the resulting component of which will be allocated as the output signal Y , depending on one or another mutual orientation of the input and output polarizers.

This Y signal is detected by a photodiode, amplified, and re-encoded into an electrical y signal suitable for further processing, storage, or transmission of information. In contrast to the classical case of the MO gate, instead of discrete signals 0 and 1, we are dealing with segments of sinusoids that serve as processed signals.

It was determined experimentally that for an alternating magnetic field of the order of 100 Oe , the rotation angle of the plane of polarization of the incident light is about 15 min/cm for a light wavelength of 440 nm .

All possible combinations of incoming X_1 and X_2 signals and their corresponding output values in the Sum y_1 and Carry y_2 channels were checked, which are shown in the truth table for the half-adder in Fig.22.

Experiments have shown that using this configuration and peripheral electronics, it is easy to achieve compliance with the values of the truth table for the classical half-adder in combination mode without any additional switching operations, as follows from further considerations.

Let's consider sequentially the processes that occur in the Sum and Carry channels, respectively.

Let two optical signals A and B from two LED s fall on the Y -shaped waveguide, as shown in Fig. 5. Passing through the polarizing filters located between the light sources and the waveguide, they are converted into X_1 and X_2 signals, polarized horizontally (HP) and vertically (VP), respectively. Generally speaking, the input signals X_1 and X_2 are purely optical in nature, its electrical representation would be a potential (*video*) signal with a voltage of the order of hundreds millivolts for the logical "1" and a voltage close to zero for "0". With the output signal, the situation is such that it is only a variable component of the light beam passed through the modulator and analyzer with a modulation frequency equal to the frequency of modulating the magnetic field created inside the waveguide by the electromagnet coil.

The Faraday rotation of the polarization plane of the transmitted light with an amplitude of α_F is carried out due to an alternating sinusoidal shape current applied to the coil. The resulting intensity of the light beam passed through the analyzer is recorded by the PDI photodiode as in Fig. 5.

The resulting photocurrent can be further divided into constant DC and variable AC components. The angle between the polarizer and the analyzer is $\pi/4$.

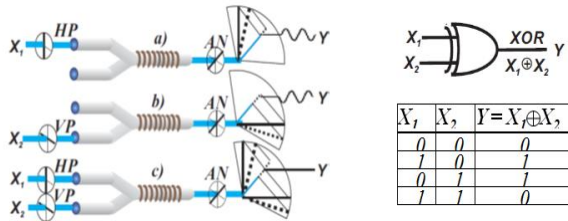


Figure 5. Diagram of a magneto-optical logic gate XOR for two binary signals processing in the waveguide *Sum* channel: a) $X_1=1$, $X_2=0$, $Y=1$; b) $X_1=0$, $X_2=1$, $Y=1$; c) $X_1=1$, $X_2=1$, $Y=0$. On the right side of the inset from top to bottom – its symbol and the truth table.

If we consider separately the situation for the X_1 (HP) and X_2 (VP) signals, we get that the photocurrent in both cases (Fig. 6a and 6b) in the absence of a magnetic field in accordance with the Malus's law will be the same and proportional to $1/2$ the initial intensity of the beam I_0 (straight horizontal lines on the inset on the right side of the figure). In the presence of an alternating current in the coil, a magnetic field occurs, leading to the Faraday effect α_F in the waveguide. For small values of α_F (Fig. 6a, 6b, and 6c, respectively), the photocurrent depends on the DC and AC components:

$$I_{ph} = k \left(\frac{I}{2} + I\alpha \sin \Omega t \right) \quad (4)$$

where k is the proportionality coefficient, I_{ph} is the intensity of the incident light, α is the Faraday rotation in radians, and Ω is the frequency of the AC generator that creates a magnetic field in the waveguide coil, $I\alpha \sin \Omega t$ – variable component of light intensity after analyzer. Thus, we have obtained a logical XOR loop for two incoming signals. The output signal in this geometry works as the *Sum* channel of the classical half-adder.

The implementation of the magneto-optical AND gate is carried out with the same geometry and with the same set of elements as for XOR , which we used for the *Sum* channel of the waveguide half-adder but the angle between polarizers and analyzer now should be chosen as $\pi/2$ or zero degree. It means that the X_1 and X_2 signals in Fig. 6 after passing through the polarizers have the same polarization axes and the same location as in Fig. 5, but the axis of the analyzer in this case is oriented perpendicular to the polarization axis of the signal X_1 and, accordingly, parallel to X_2 .

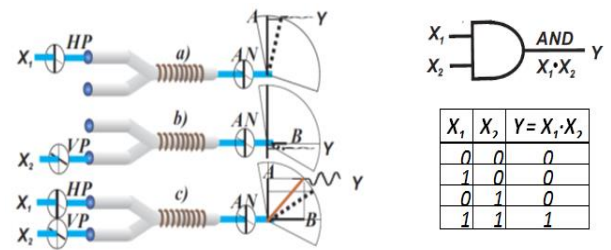


Figure 6. Diagram of the magneto-optical logic AND gate, for processing two binary signals in the transfer channel: a) $X_1=1$, $X_2=0$, $Y=0$; b) $X_1=0$, $X_2=1$, $Y=0$; c) $X_1=1$, $X_2=1$, $Y=1$. On the right side of the inset from top to bottom - its symbol and the truth table.

In both cases (Fig. 6 a and 6 b), when there is one signal (only X_1 or only X_2), the output variable signal will be zero, as shown in the corresponding insets. This can be proved more strictly by simple trigonometric transformations for small angles of Faraday rotation. If both signals are presented, we get a sinusoidal response, which can be assigned the value 1.

In order for the XOR and AND operations to take place simultaneously in the same waveguide, it is enough to combine Fig. 5 and Fig. 6 and switch from the Y configuration of the waveguide to X , as shown earlier in Fig. 3.

III. CONCLUSION

The proposed method of quantum information processing radically changes the situation with the element base of logical devices. There is no need to use bulky and expensive elements, such as high-quality mirrors, translucent plates, crystal polarizers, phase plates, optical benches and light sources. All processes are localized within a single waveguide element, a fraction of a square centimeter in size, using the obvious advantages of fiber and integrated optics [7-9]. It seems appropriate to actively continue the research that has been initiated in order to apply the results in the applied fields of Artificial Intelligence and communication technologies.

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