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PHOTONIC INTEGRATED CIRCUIT AND ITS CALIBRATION

The article proposes a new structure of a photonic integrated circuit for multiplying vector signals by a matrix. The architecture and principles of operation of modern photonic integrated circuits according to the given classification are briefly described. The proposed system consists of three layers, which includes a radiating, receiving and intermediate block with apertures. The connection of the photonic integrated circuit to the necessary electrical circuit for the investigation of the output signals of the photonic integrated circuit is described. With the help of the electrical circuit, we can monitor and control the input signals on each waveguide of the radiating unit, and track the change of the output signals that have passed through the system and fixed at the output of each waveguide. In the course of the study, we develop graphs of the levels of input and output signals of the system. With the help of which we represent the system errors and the change of signals, which makes it possible to calibrate the system. Calibration of the photonic integrated circuit is carried out by calibrating all electrical elements of the radiation and the receiving unit. In the emitting unit, it is necessary to select the same LEDs according to their characteristics, and with the help of variable resistors, which are connected to each pair of LEDs, calibrate the LED to the same brightness. We control the uniformity of brightness with the help of an IR camera. To calibrate the receiving unit, we fix the shadow noise and enter the reference coefficients for each receiver. After all the units were configured, the system was tested. A block with a specific aperture location was created, and the output signal was removed. Based on the results of the study, we proved that the system calibration is correct and that the system is operational.

Keywords*: photonic integrated circuit, multiplication of vector by matrix, optical waveguide, PIC research, photonic devices, optoelectronics.*

ІРИНА АВДЄЙОНОК, ВОЛОДИМИР БОРОВИЦЬКИЙ
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ФОТОННА ІНТЕГРАЛЬНА СХЕМА ТА ЇЇ КАЛІБРУВАННЯ

У статті запропонована нова структура фотонної інтегральної схеми для перемноження сигналів вектора на матрицю. Коротко описано архітектури та принципи роботи сучасних фотонних інтегральних схем за приведеною класифікацією. Запропонована система складається з трьох шарів, яка містить випромінюючий, приймальний та проміжний блок з апертурами. Описано підключення фотонної інтегральної схеми до необхідної електричної схеми для проведення дослідження вихідних сигналів фотонної інтегральної схеми. За допомогою електричної схеми ми можемо моніторити та контролювати вхідні сигнали на кожному хвилеводі випромінювального блоку, та відстежувати зміну вихідних сигналів, що пройшли через систему та фіксуємо на виході кожного хвилеводу. В ході дослідження отримаємо графіки рівнів вхідних і вихідних сигналів системи. За допомогою яких виявляємо похибки системи та зміну сигналів, що дає можливість відкалібрувати систему. Калібрування фотонної інтегральної схеми відбувається шляхом калібрування усіх електричних елементів випромінюючого та приймального блоків. У випромінювальному блоці необхідно відібрати LED однакові за характеристиками, та за допомогою змінних резисторів, які приєднані до кожної пари світлодіодів, відкалібрувати LED до однакової яскравості. Рівномірність яскравості контролюємо за допомогою ІЧ камери. Для калібрування приймального блоку фіксуємо тіньовий шум та вносимо поправочні коефіцієнти для кожного приймача. Після того як було налаштовано всі блоки, зроблено тестування системи. Було створено блок з певним розташуванням апертур, та знято вихідний сигнал. За результатами дослідження ми довели, що калібрування системи правильне та що система працездатна.

Ключові слова: фотонна інтегральна схема, перемноження векторів на матрицю, оптичні хвилеводи, дослідження ФІС, фотоні пристрої, оптоелектроніка.

Introduction

Photonic integrated circuit (PIC) [1-3] is a device into which several optical components are integrated such as interconnect waveguides and optical amplifiers, integrated onto a single chip built on a compound semiconductor substrate. Photonic integrated circuits are typically fabricated using wafer-scale technology (using lithography) on substrates (often called chips) of silicon, silica, or a non-linear crystalline material such as lithium niobate (LiNbO3) [4-5]. Photonic integrated circuits can be used to create faster and more energy-efficient devices. This is because these PICs can receive data with a high level of accuracy and are very efficient in data processing and transmission. They are also integrated with traditional electronic chips and applications.

Photonic integrated circuits have high performance of vector calculations and low power consumption. They can be classified into 2 groups[6]. In single-layer PIC, active elements are located in the plane of optical waveguides. In multilayer PIC, active elements are located between layers of optical waveguides.

There are two types of multi-layer PIC. In the first case [7-9], powerful light sources such as lasers are used. The line of lasers is located perpendicular to the line of receivers that fix the output signal. Between them is an active element, thanks to which matrix calculations are performed. The active element can act as an array of diffraction elements, electrochromic films, an array of spatial light modulators.

The advantage of such a structure is work in parallel mode, which ensures high speed. However, the disadvantage is high complexity, high cost and limited accuracy.

In the second variant [10-11], the waveguide structures are arranged perpendicularly. An active element is placed between the waveguides, such as photochromic or diffraction elements. The input reaches the upper layer of the waveguide, the output signal is fixed from the lower layer of waveguides. In this way, cells with access to each element are formed. This structure is economical due to the ease of manufacture, but it does not have high accuracy.

3 main structures can be distinguished in planar PICs.

The first group uses a microring resonator [12,13]. First, the input optical signal is modulated and multiplexed. Then, for given wavelengths, the transmission of optical signals changes according to the matrix coefficient. In this way, the output signal is formed so that each output signal has a certain wavelength, and its amplitude is proportional to the multiplication of the amplitudes of the input signal by the coefficients of the matrix row.

The second design uses a spectral filter to control each connection [14,15]. The input optical signal is formed by a laser source, which is subsequently multiplexed and split into optical signals with different wavelengths. A spectral filter is used at the input of each block. The filter is configured on the receiver and selects the active connection. The advantage of such a structure is the possibility of parallel multiplication. However, they are highly valuable and sensitive to temperatures due to their complex topology.

The third design uses a Mach-Zehnder interferometer [16,17] in the nodes and has two interference arms in the form of optical waveguides. In one arm there is a phase-shifting device. The MZI matrix core has great promise for increasing matrix computing functionality and versatility. But it has disadvantages due to the large area of the entire structure and additional energy consumption.

Goal and tasks

Purpose: to propose a new design PIC for fast matrix-vector operations and to investigate the characteristics of this PIC**.**

Tasks: to design and investigate a multilayer PIC. Namely, to investigate the levels of the signals supplied to the circuit and the levels of the output signals, as well as the changes in the output signals when controlling the inputs. Such a study is necessary to prove that the PIC can perform matrix-vector operations with sufficient accuracy.

Methods

Structure PIC

The proposed PIC scheme uses optical waveguides in which radiation is scattered multiple times, and an intermediate block of apertures that changes the optical flux of radiation for each waveguide. The proposed scheme consists of three blocks (fig.1a):

- the first block – emitter block 1 contains light emitted diodes (LEDs) and the input optical waveguides;
- the second block 2 is the holder of the film 3 with apertures;
- the third block – receiver block 4 contains the output optical waveguides with photodetectors.

The structure of the first and third blocks is similar (fig.1b). It includes housing 5, reflector plate 6, two boards with LEDs or photodiodes 7, optical waveguides 8 and cover 9 that fixes all elements 5 – 8 together.

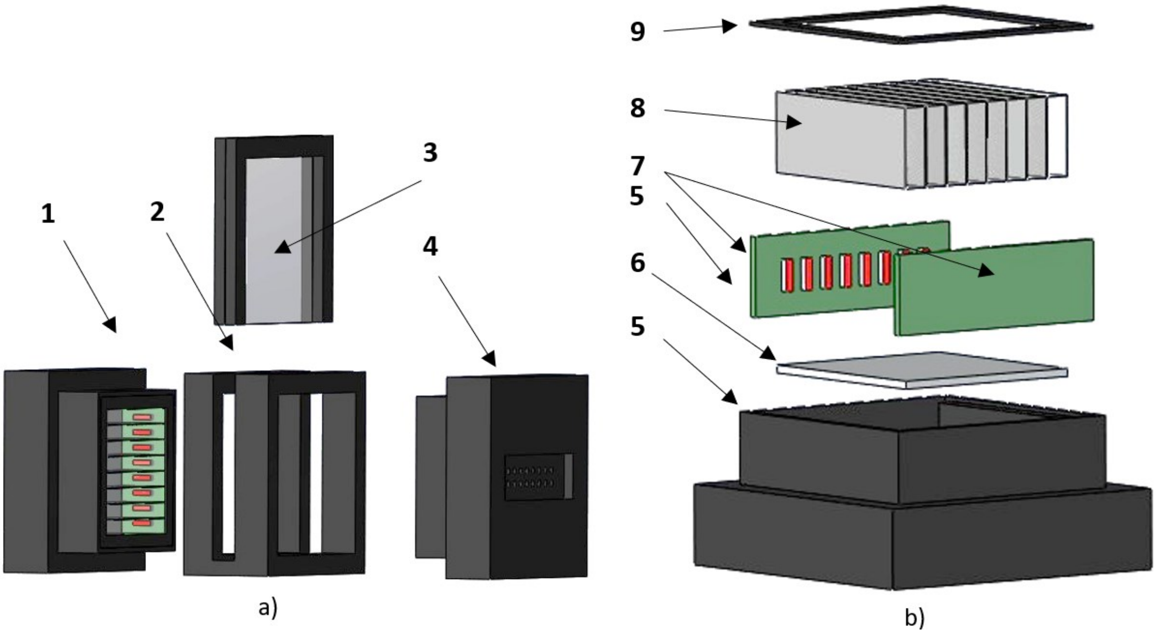

Figure 1. a) proposed PIC design, b) proposed design of emitter and receiver blocks

This PIC performs operations of multiplication of vectors by a matrix using optical signals. The vector of the input optical signals comes to the input optical waveguides. They passed through the film 3 with aperture matrix. The area of apertures is proportional to the matrix coefficients, that is the energy of the passed optical radiation becomei proportional to the aperture area. The output optical waveguides collect the passed optical radiation and they form the output optical signals. These output optical signals are proportional to the result of multiplication of the input optical signal to the matrix.

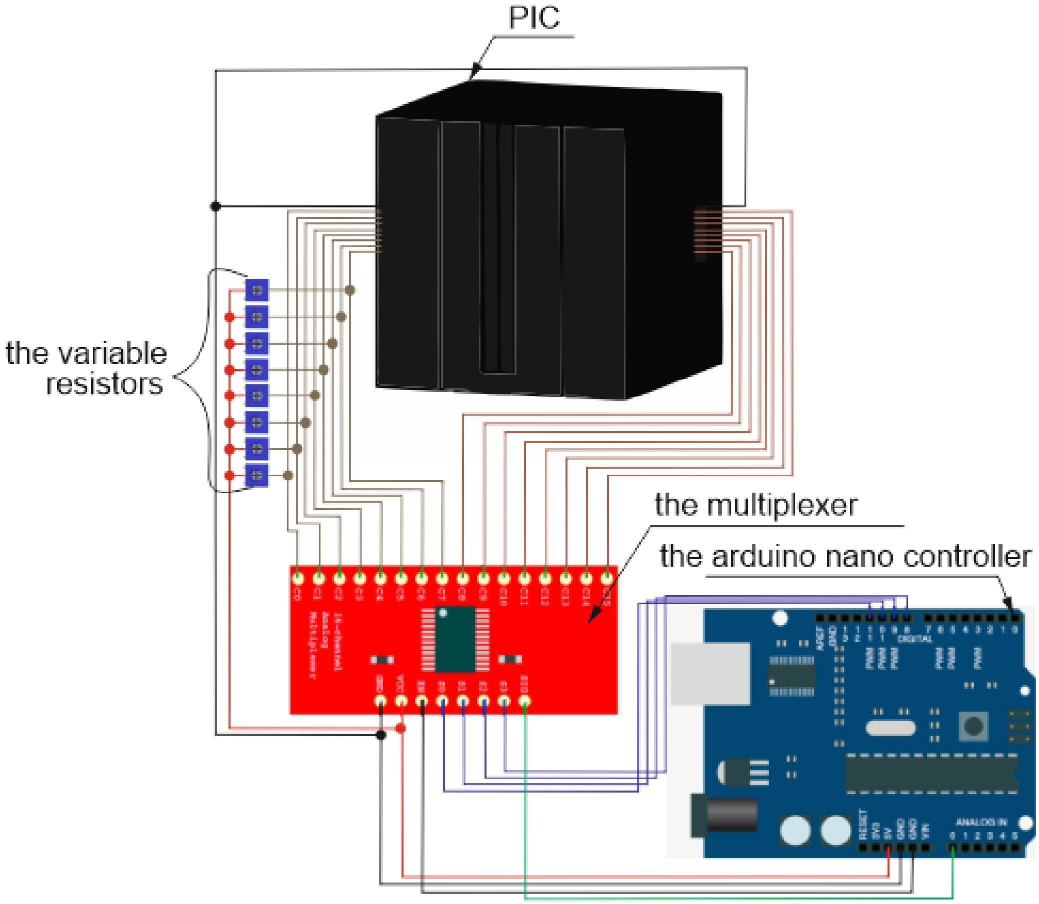

Figure 2. Electronic system for PIC investigation

Electrical circuit connection PIC

To conduct the research, we connected the PIC to the electrical circuit. The picture (fig. 2) shows the connection diagram. With the help of variable resistors, we can change the input signal to LEDs that emit light into each waveguide. To fix the signal levels on the LEDs and the received signals from the waveguides, we connect the PIC to the analog inputs of the Arduino nano controller. Since the controller has only 5 analog inputs, and the signals we read are 16 (8 signals are the signal levels on the LEDs, the other 8 are the signal levels on the receivers). Therefore, we connect the PIC to the multiplexer CD74HC4067, and we connect it to the Arduino controller.

For monitoring and graphical display of received signals, connect the controller to a PC. With the help of the software, we monitor the input signals and monitor the change in the output signals from the PIC.

A vector multiplier stand was developed, which includes a PIC and a controller, a multiplexer.

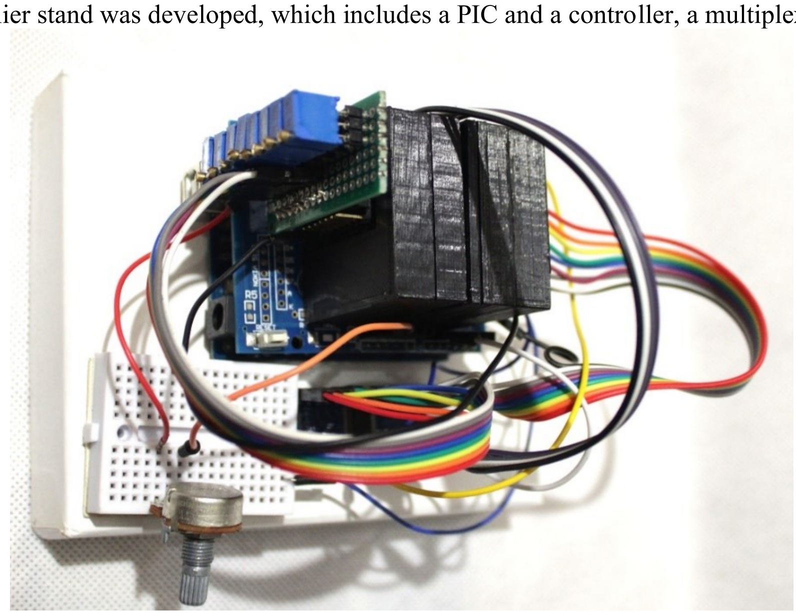

Figure 3. Photo of PIC prototype

Result

To carry out accurate measurements, we fix the dark signal from the photodetectors without PIC input signal.

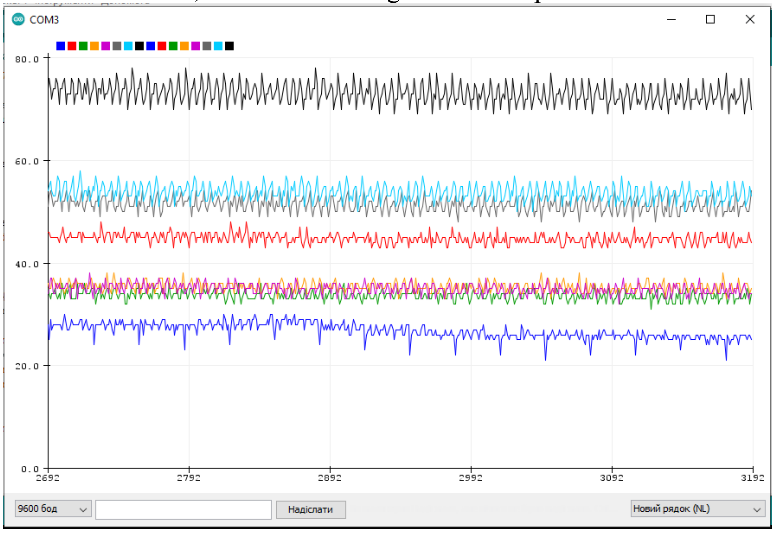

Figure 4. Graph of dark noise monitoring of receivers

The next step was to apply the same input signal level to each waveguide.

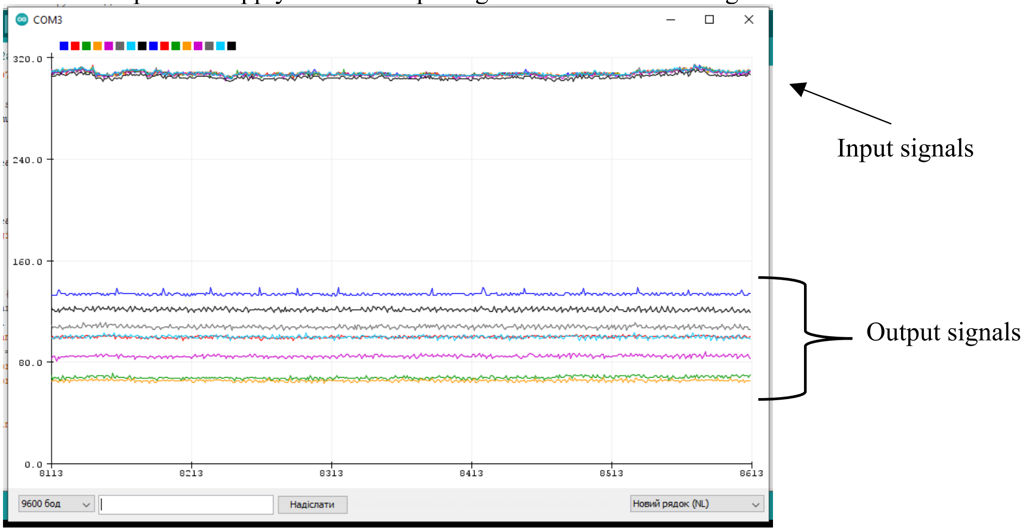

Figure 5. PIC signal monitoring schedule with the same input signal

The next step is to change the input signal on each waveguide so that they are different. We will get the graph and the next one with an decreased signal level.

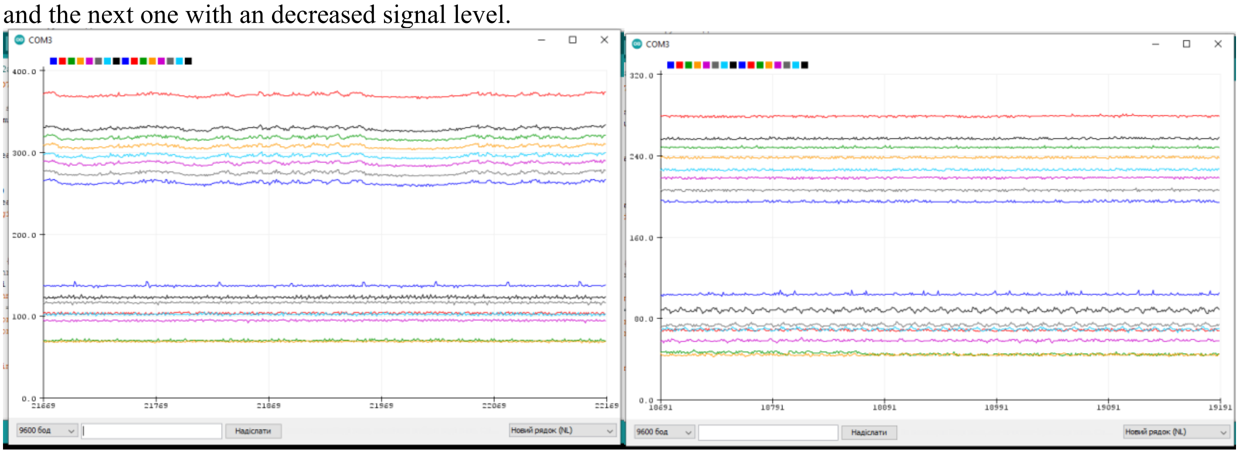

Figure 6. PIC signal monitoring schedule

With the help of an additional variable resistor, we can control the input voltage to all LEDs. Due to which we change all 8 input signals at the same time and monitor the change of 8 output signals PIC.

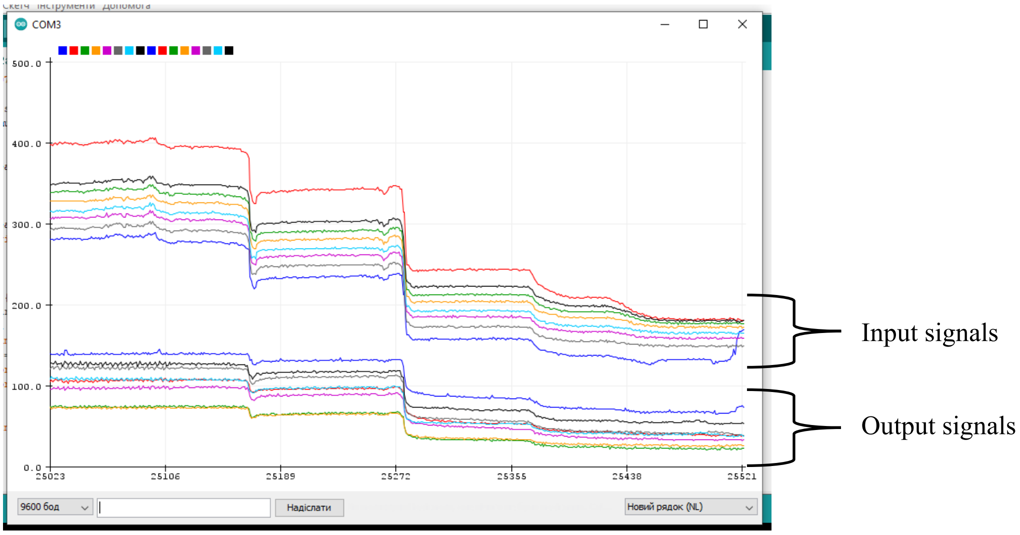

Figure 7. PIC signal monitoring when the input signals change

In the course of the research, it was found that the different sensitivity of the electrical elements causes differences in the output signal from each waveguide. It is necessary to calibrate the circuit due to built-in resistors for each signal or by selecting photodiodes with approximately the same parameters.

Calibration

To calibrate the PIC, it is necessary to set the same input signal (fig. 9). To do this, we equalize the brightness of the LED by adjusting the input electrical signal with variable resistors (fig.2). We also make the aperture matrix with the equal hole sizes (fig. 8).

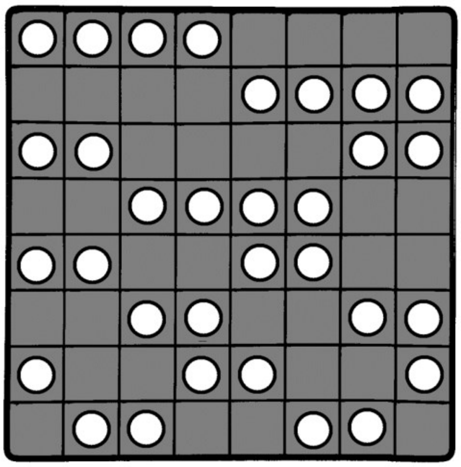

Figure 8. Pattern of the aperture matrix

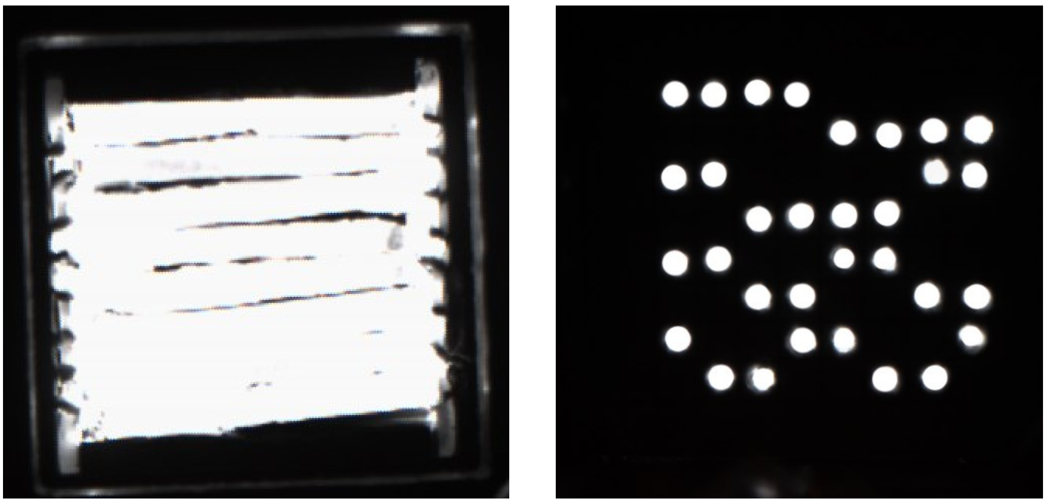

Figure 9. Photo of configured LEDs and illuminated variable aperture matrix

Table 1

Calculations of mean deviation of PIC signals

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	Average
No aperture matrix	-0.012	-0.018	0.003	-0.004	0.028	-0.002	-0.005	-0.003	0.013
Aperture matrix	0.151	0.123	0.158	0.063	0.142	-0.134	-0.119	-0.150	0.129
Reversed aperture matrix	0.145	0.119	0.164	0.074	0.165	-0.122	-0.117	-0.154	0.131
Calibration coefficients	**0.87**	**0.89**	**0.86**	**0.93**	**0.86**	**1.14**	**1.13**	**1.18**	

The average deviation of the values is 1% without the aperture matrix, because we reach the saturation level of photodiodes (table 1). With aperture matrix, the average deviation increases up to 13% due to different sensitivity of the photodiodes. The obtained data helps to calculate the calibration coefficients that guarantee the highest accuracy of optical multiplication of vectors to matrix. The data about different characteristics of LEDs and photodiodes should be considered during the design of aperture matrix to maximize accuracy of optical multiplication.

Discussion

The proposed PIC was manufactured, assembled, and investigated. The special electronic system based on Arduino minicomputers was used for sending input signals and registration of output signals of the PIC. This system makes possible fully automatic PIC testing under computer control. The experiments help to identify the factors that decrease accuracy of optical multiplications: variations of LEDs characteristics, variation of photodetector characteristics, non-uniformities of optical properties of waveguides. Influences of these factors can be compensated by PIC calibration and the corresponded design of aperture matrixes.

Conclusion

It is proposed the new PIC design for optical multiplication of vector to matrix. This PIC contains three layers: the layer of input optical waveguides, the layer of aperture matrix and the layer of output optical waveguides. It was designed, assembled, and tested the working prototype of the proposed PIC. It was proven that the calibration of such PICs is necessary due to variance of LEDs and photodiodes characteristics. The proposed setup and calibration procedure make possible setting the input optical signal, registration of output optical signals and calculation of calibration coefficients. The performed research shows that the proposed PIC can be applied for analog optical multiplications of vectors to matrix. This economical PIC may be implemented for fast calculations and hardware realization of neural networks with small number of neurons.

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