To the issue regarding the content of the future specialists training in the field of modern optics and photonics

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Abstract. The article is a continuation of the authors' works on the problem of achievements presentation of modern physics to future teachers and physics students. It deals with the issues related to the necessity explanation of the transition from electronic circuits to optical ones and technologies of optical circuits development. Moreover, the article shows the ways to motivate students to study physics and conduct experimental research. One such a way is to involve students to real scientific research. As a result, they can feel the importance of their contribution to the work of the group of researchers and appreciate the benefits of collective forms of work. The authors emphasize that nowadays professors and students have new opportunities associated with the access to new information and computer technologies, as well as greater the availability of rather complex physical equipment. The accessibility is connected with the organization of centers for common usage equipment, remote access to various databases of connected with results scientific research. All of the mentioned issues create favorable conditions for the further attempt to familiarize students with the problems of modern science.

1. Introduction

Nowadays, the problem of conversance of future physicists-researchers, engineers, as well as professors and teachers with the problems of modern physics is very urgent in education. Since at the majority of universities the number of hours devoted to physics studies is steadily decreasing, it is obvious that this problem can be solved through special workshops or special courses (for Bachelor's degree), as well as through courses developed for specialized master's programs.

A much more interesting aspect of this problem is the content of the lessons, as the amount of material that students would like to introduce is extremely large. It is obvious that there will always be some specifics in the choice of direction, related to the profile of training at a particular university, as well as its material capabilities.

However, there are some issues in modern science that are quite relevant for students studying in fields related to modern physics. For example, such problems may be as follows: problems of information transfer and creation of modern electronic devices. Why are particular these issues considered? First of all, we live in the period of time when information is spreading avalanche-like. It means that we need to understand what makes it happen. We use a large number of gadgets; so, a modern specialist should understand at least the general principles of these devices. It is necessary
both for proper use of such devices and for adequate choice of the most necessary ones for effective problems solving.

Secondly, modern technical capabilities make it possible to involve students into the practical study and, in some cases, even to develop the most complex electronic circuits.

A lot of universities found scientific divisions at their departments, equipped with quite modern scientific equipment. Moreover, the development of the idea of accessible technoparks also contributes to the availability of modern equipment and the implementation of innovative projects.

The given article will tell about the experience of teaching modern physics at Moscow Pedagogical State University. It is possible to get more information about such lessons organization in [1].

First of all, students should identify the key points in the electronics development and the way that has been taken over a period of time slightly exceeding one hundred years. It is necessary to show that the development of electronic devices in recent years has been extremely rapid. New technologies and algorithms have appeared. They have been aimed at increasing miniaturization of schemes used in them. This was caused by the first quantum revolution in the twentieth century resulted in the development of quantum mechanics and laws of the atomic world were understood. This new scientific knowledge led to the introduction of the transistor and laser, study of radioactive decay, development of quantum theory of electromagnetic wave radiation, etc. The peculiarity of the first quantum revolution was the emphasis on the application of the collective quantum phenomena. One can assume that nowadays physics is going through the epoch of the second quantum revolution. Its essence is to consider the possibility of controlling quantum systems with the help of separate particles (electrons, photons). As a result, completely new areas start to develop. Fundamental research in quantum physics allowed to realize a fast Internet only one example. This has radically changed all spheres of our entire life, i.e., social, economic and political.

The main element for quantum systems development is special electronic circuits. However, there are more and more acute problems due to the reduction of their planar sizes. They are associated with the movement of electrons. At present, all structures have reached a nanometer scale, and electrons cannot be considered only as charged particles. It is necessary to describe them in the language of wave functions, spins, etc. In this regard, it is also obligatory to take into account various limitations, in particular those facts that the bandwidth for the signals transmission cannot be very wide and significant impact on the operation of electromagnetic interference schemes.

Together with the students we came to the conclusion that it is impossible to improve electronic chips further; it means that some other way, another principle should be found. And it was found; these are optical circuits based on the use of photons, not electrons.

The listed above restrictions are not applied in optical schemes. Such circuits are not sensible to interference, the signal transmission over the optical channel is low loss, and the bandwidth currently reaches Tbit/s.

The first circuits allowing quantum-optical information processing were created on a special beam table. But nowadays the number and complexity of optical circuits have significantly increased. The requirements to temperature stability of all components of the circuit as well as their mutual location, power consumption and energy losses have been increased. For these problems solving, the task was set to combine all the components on a single substrate (a system on a crystal, System on a chip) so that the function of the whole equipment to process optical signals (now it is more relevant in the near infrared wavelength range) performed. In this case, the quantum-optical chip will not require adjustment and all its components will be fixed relative to each other.

Now let's recall, what was all this done for? The answer is to miniaturize a circuit. Quantum-optical circuits satisfy this requirement absolutely as all their elements have micron or even submicron dimensions. However, this type of equipment has disadvantages as well. The main one is the complexity of mutual conversion of optical and electrical signals. Another disadvantage is difficulty of integrating optical circuits. The priority is input and output of radiation from optical elements. A new field of physics, i.e., nanophotonics, offers methods of its solution. At present, they have a progress in this problem solving, but they also have serious limitations.
Further we should discuss the peculiarities of complex photonic integrated circuits development by means of modern nanotechnologies. It is possible to produce compact devices on a chip on their basis. Photonic integrated circuits have some advantages over those implemented on abeam table. They are low optical losses, no need for optical alignment, insensitivity to vibration, small size, weight and power consumption, but the most important is their scalability [2].

Such quantum optical microcircuits can be used in quantum cryptographic data transmission systems, quantum metrology. They are also indispensable for modeling complex molecules (quantum simulators allow, for example, calculating coupling energies in molecular compounds). Moreover, they can significantly increase the computation speed and data processing (linear quantum computer). Modeling the properties of complex chemicals is extremely urgent issue which stands in quantum chemistry. This field of research is directly related to the development of quantum computers. It can provide new opportunities for calculating the properties of individual molecules (e.g., their spectra). It is directly related to the search for new medicines and materials. Now that the goals and possible applications of optical chips are clear, we should move on to a more detailed discussion of the technology of their development.

2. Optical planar wave guides

Currently, more than ten scientific groups around the world are working on fully integrated optical circuits that combine all the necessary components from the light source to the detector. Various waveguide materials are applied to create these optical microchips: silicon oxide, silicon, gallium arsenide, polycrystalline diamond and silicon nitride (Si₃N₄). Each of the applied materials has its advantages and disadvantages, that is why, the work is being carried out with all materials simultaneously [3, 6]. A value of about 1550 nm has been chosen as the working wavelength, since at this wavelength there is minimal absorption in most of the materials used, as well as no material dispersion.

In our opinion, it is expedient to conduct an excursion to the laboratory of the university, where they could be engaged in this problem solving to motivate students to further study this scientific area in modern physics. It would be useful to demonstrate modern research equipment and photographs of ready-made equipment. It may be worthwhile to talk to postgraduate students working on this problem. This will help students to feel their involvement to problems that are important for modern physics. Then, we can tell about the laboratory.

In the studies conducted at the Moscow Pedagogical State University (MPSU), silicon nitride (Si₃N₄), which has low optical absorption in the infrared and visible spectrum ranges, is used as a waveguide material. Moreover, this material has good mechanical properties and high refractive index (n = 1.98) [4]. This material can perform several functions at once. It is the basis for radiation sources creation on the chip [5, 7], individual elements [7, 8] and integrated single-photon detectors on the chip [8, 9].

The refractive indexes of silicon nitride and silicon dioxide are noticeably different. This makes it possible to create waveguide structures with a small swivel radius and significant radiation power in the waveguide.

One of the main tasks in developing quantum integrated circuits consisting of different materials is the development of technology in which the subsequent stages of device formation would not lead to degradation of components manufactured at the previous stages. In this regard silicon nitride has also advantages, since the planaroptical elements based on it can be produced in the laboratory using electron-beam lithography. Silicon nitride will then act as the core of the waveguide, and the widespread silicon oxide can be used as a shell.

Modern integrated quantum-optical circuits are the main elements that provide signal transmission between different, embedded in the chip elements with high efficiency and low loss. Moreover, students should pay attention to the fact that, unlike traditional waveguides, which consist of fibers with concentric symmetry, in quantum-optical microcircuits, uses a different spatial configuration of
elements, which is a layer of the thinnest film applied to the substrate. The principle of total internal reflection is the basis for any type of waveguides.

The planar waveguide is a guide system for radiation in the form of a thin film on a dielectric substrate. The film thickness $h$ is comparable to the wavelength $\lambda$. From this film a narrow strip is formed in the direction of light diffusion. The refractive index of such a strip is greater than that of the areas surrounding it. As a rule, materials are isotropic, so the refractive index $n$ depends only on the cross-section of the waveguide.

Consider the condition when light will be fully reflected on the interfaces of media in the waveguide structure. The angle of incidence of light on the interface between air and waveguide must exceed the value $\theta_{ci}$ satisfying the following condition:

$$\theta_{ci} = \frac{1}{\sin \left( \frac{n_3}{n_2} \right)}$$

Figure 1. Schematic representation of a planar waveguide. The condition that the refractive indexes $n_2>n_3$ and $n_2>n_1$ must satisfy. If this condition is satisfied, light spreads in the layer with the highest refractive index $n_2$.

Radiation in such a structure will be concentrated in the core of the waveguide (material with a refractive index $n_2$), due to the complete reflection from the interface boundaries. For this, critical angles must meet the condition $\theta_2>\theta_3>\theta_1$. We can decompose the light wave reflected backward and forward inside the core into two mutually perpendicular waves to explain it clearly (Figure 2). As a result of this representation, a part of the wave moves along direction $x$ with the wave vector $k_x = k \sin \theta$. The second part is distributed in parallel to $z$ with the wave number $k_z = k \cos \theta$ and reflected when hitting the boundary. This part of the wave interferes reflecting from the horizontal boundaries. Depending on the phase, the intensity of the wave per single pass inside the waveguide is either equal to the maximum interference or to the minimum one.

Figure 2. The upper figure shows schematically the reflection of light with an angle of incidence $\theta$ from the boundaries in a flat waveguide with a core height of $d$. The lower figure shows that the wave front can be represented as two mutually perpendicular waves moving in the direction of the $x$ axis with the wave vector $k_x$ in the direction of the $z$ axis with the wave vector $k_z$. 
The total phase shift determined by interference, can be written as:

$$\Delta \phi = 2dk \cos \theta + \varphi_1(\theta) + \varphi_3(\theta),$$

where $\varphi_1$ and $\varphi_3$ are phase shifts resulting from reflections at the lower and upper interfaces, respectively. The condition for phase shifts must be satisfied for all radiation concentrated in the waveguide:

$$\Delta \phi = 2m\pi,$$

where $m$ is an integer.

![Figure 3](image1)

**Figure 3.** a) Schematic of the light distribution in the optical waveguide; b) results of numerical simulation of the electric field distribution inside the waveguide made of silicon nitride, performed in the program High Frequency Structural Simulator, HFSS.

Figure 3a shows a longitudinal section of the dielectric waveguide with $n_{wg} > n_1 > n_2$. The Figure illustrates the phenomenon of total internal reflection and the condition for its observation mentioned earlier, i.e., the existence of the maximum angle of the radiation incidence on the interface between two media $\theta_m$. The light is reflected from the interfaces and distributed within a high refractive index ($n_{wg}$) without loss. The limiting angle is called the Brewster angle [5].

This description is made according to the geometric optics approach. A rigorous analysis based on the solution of the Maxwell equations with boundary conditions helps to explain in detail the effect of the total internal reflection in the waveguide and more complex phenomena associated with light tunneling or modal coordination [10, 11]. To obtain the distribution of electric field inside the waveguide and to obtain the results of solving Maxwell's equations at selecting the optimal geometric dimensions, determining the effective refractive index, as well as the transmission and reflection spectrum of the developed structures, use numerical simulation based on the finite element method (figure 3b).

![Figure 4](image2)

**Figure 4.** a) Scheme of waveguide structure layers; b) ridged waveguide; c) strip waveguide.

Planar waveguides can be of two types: ridged and striped (fig. 4). Ridged waveguides are formed from partially etched waveguide layer profile, strip waveguides are formed from fully etched profile
[12]. In researches carried out at MPSU, a ridged waveguide is mainly used. This choice is due to the small size of the side waveguide wall, which is the main optical loss caused by light scattering on its heterogeneity.

So, we have considered how radiation in real waveguide chips spreads in two dimensions. This consideration is important for combed waveguides like the one shown in Figure 4. For ridged waveguides, the refractive index depends on both the size of the waveguide in the y axis and the size of the z axis (figure 5). As a result, the electromagnetic field appears to be concentrated in the core of such a waveguide.

An example of such a simulated wave for a silicon nitride waveguide located over a silicon dioxide layer with typical dimensions is shown in figure 5. It also shows the finite element splitting grating used for this calculation.

![Figure 5](image)

**Figure 5.** Simulation of silicon with a height of 450 nm and a width of 1 μm. Left: field profile of the fundamental TE-like mode with $n_{\text{eff}} = 1.587$. Right: grating used for this calculation.

3. **Main elements of optical integrated circuits**

   The elements of optical integrated circuits can be divided into three main blocks: a block of radiation sources (single photon sources), a block of processing elements, signal conversion and a block of detectors.

   The creation of a highly efficient single photon source on a chip is an important task in the development of optical integrated circuits. One of the main problems for such sources is effective suppression of pumping power. For this purpose, it is necessary to use high efficiency filters capable of suppressing radiation with efficiency up to $10^{12}$ times. These filters must be placed in the same circuit on the same chip as the source. One of the realization variants of such an effective filter on the chip is a planar Bragg waveguide. It can be used to solve the mentioned problem [13]. Planar Bragg waveguide can also be applied as a separate element of optical integrated circuits for radiation filtration.

![Figure 6](image)

**Figure 6.** a) Image of the Bragg waveguide for further manufacturing by electron-beam lithography. b) Enlarged image of the Bragg waveguide. c) Enlarged image of the focusing lattice element of communication.
In quantum optical integrated circuits, other elements of integrated optics are also required (such as focusing coupling elements, dividers, resonators, etc.). A frequently used element of such circuits is a tap; it makes it possible to make a multi-channel circuit, thereby to increase its efficiency. One of the possible alternatives for a coupler on a chip is an anti-directional coupler based on a Bragg waveguide. Such couplers not only divert part of the radiation propagating in the circuit to another channel, but also divert a given wavelength range, almost completely cutting it out of the main channel, while practically not changing the power of the transmitted radiation. Multichannel demultiplexers, equipment for separating channels with optical signals of different wavelengths can be created on the basis of these couplers [13].

The light signal control is much more complex than the electrical signal control. This is due to the fact that the photon has no electrical charge. The problem can be solved with the approach of micro- and nanostructuring of elements in the photonic integrated circuit. Physically, this means the application of the complex dielectric constant distribution, leading to diffraction and interference of light and hence to the desired field distribution. A special case of the control problem by a light signal is the problem of input (output) radiation into a dielectric waveguide from the optical fibre of an optoelectronic circuit. This problem is standard and it is solved in developing some photonic integrated circuits. The diffraction method has received the most widespread and development among other alternatives. The key element is the diffraction grating-type input equipment (Focusing Grating Couplers, FGCs). Its operating principle is based on changing the wave vector of photons by the reciprocal grating vector when radiation is introduced into the waveguide.

The basic principle of radiation input into the waveguide is the phase and amplitude matching of the optical signal in the fibre and the optical signal in the waveguide. The phase of the optical signal in the waveguide is proportional to \( \exp(-\beta z) \), where \( \beta \) is a number called the propagation constant. In its physical meaning, it is a component of the radiation wave vector directed along the waveguide. Due to the fact that the conditions of total internal reflection are fulfilled during wave propagation along the waveguide, the propagation constant in absolute value is greater than the wave vector of the wave in vacuum. This makes it impossible to enter without additional tools. This barrier is overcome by interaction with the diffraction grating of the input device. It can "add" the incident radiation \( \beta = k_x = \frac{2\pi}{\lambda} \sin \phi \) of the vector \( \frac{2\pi}{T} \) to the horizontal component (figure 7). It is possible to achieve the coincidence of the coordinate dependences of the phases of the incident wave and the wave in the waveguide choosing the required grating period \( T \). It leads to the effective radiation input.

![Figure 7. Diffractive interaction of radiation with a grating. The first diffraction order resonates with a wave of the waveguide](image)

The evaluated input efficiency for these parameter sets is 70% and 52%, respectively.


Figure 8. Distribution of the electromagnetic field at radiation introduction (isometry).

Figure 9. a) Electronic form of the input / output diffraction grating without apodization; b) an electronic form of the input / output diffraction grating with apodization. (Apodization is an action on an optical system that leads to a change in the intensity distribution in a diffraction image).

4. Manufacturing of quantum-optical integrated circuits

Dielectric fibres are manufactured by methods applied in micro and nanoelectronics: cathode sputtering of the waveguide material onto a substrate, epitaxial overgrowth from a liquid or gaseous phase, or by the method of ion implantation [3].

The task of the technology is to form waveguide layers of the required thickness and create the topology of individual elements of a quantum-optical microcircuit.

Dielectric layers are formed on substrates. In the case under discussion, silicon is used as the substrate. But the range of materials used is wide; lithium niobate and tantalite are also applied. Sometimes a method of increasing the refractive index of the near-surface layers of the substrate by radiation, chemical, thermal, or other effects is applied [3].

It is necessary to apply photolithography or electron beam lithography to form the individual planar elements and units of the microcircuit.

Consider the technology of manufacturing planar waveguides, which uses multilayer dielectric structures on a silicon substrate, by forming two layers, i.e., a silicon dioxide layer and a silicon nitride layerSi/SiO₂/Si₃N₄ (Figure 10). The size of the silicon substrate is 15×15 mm.

The thickness of the silicon dioxide layer is 2.6 μm. The refractive index at 1550 nm is approximately 1.47.
There is a layer of silicon nitride. The elements of a quantum-optical microcircuit are created using electron lithography formed from it on silicon dioxide. The thickness of the nitride layer is 450 nm. Its roughness, measured with an atomic force microscope, does not exceed 4 nm. The refractive index of silicon nitride for a wavelength of 1550 nm is approximately equal to 2 [4, 6]. Various elements of quantum optical integrated circuits are shown in figure 11.

**Figure 10.** Silicon wafer structure.

**Figure 11.** Picture of elements of the integrated optical microcircuit.

**Figure 12.** The three upper figures are photo micrographs from an optical microscope. The next six images were obtained with an electron microscope where one can see the details of various elements of integrated optical circuits [12-14].
5. Conclusion

However, the serious scientific problems solving shows that this confidence is somehow excessive, and the possibilities of modern technology are much wider. Thus, students feel cognitive dissonance.

A lot of students pursue to deepen their knowledge both in the field of modern physics and in the field of computer modelling; they work with pleasure, and this leads to respective results.

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