The control system elements of the new generation optical switching cell

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Abstract. In this paper calculation of new optical switch parameters that allows us to create next generation all-optical non-blocking switching system without external control devices is carried out for the first time. In particular, switching cell control device is studied in detail. The presented one includes Bragg filter, frequency detector, optical isolator, and former of a control signal. Here we also present the detail description and the numerical calculations of these devices for third transparent window (1550nm). The reflection and transmission coefficients are obtained, the passbands of the Bragg filter are presented, and the amplitude characteristic of the frequency detector is calculated.

1. Introduction

Due to the increasing requirements for the throughput of telecommunications networks, the optical switching system design becomes important and interesting problem [1-8]. For today, various architectures of such systems have been presented in the scientific literature [1,4-6]. As rule these systems are built on 2x2 switching cells [1,4-5]. However, such an approach gives us unwieldy multi-stage systems of great complexity [1,3,5]. Moreover, the additional disadvantage of current optical switching systems is so call blocking [3]. As a result, the ones need special control algorithms and must use buffer devices. On other words information must be transform from optical to radio domain and back. Additionally, 2x2 switches as rule based on nonlinear optical effects [1] that pulls down system performance. Therefore, the creating all optical switching cells is very important problem of modern optoelectronics.

Today, there are only few scientific papers that describe all-optical switches without external control devices based on linear optical effects only [1,4,6]. For example, it has been developed new type of switches base on 4x4 and 8x8 cells [7,8] with relatively low complexity. The main feature of those optical switches is the control method. Note that in general a connecting path between input and output can be set by external control unit or it can be determined by control switching elements inside the system. In [4,6] the authors have presented the structure of optical cross switches controlled by external device. But existing external control devices are electronic and obviously limit a speed of that optical switching. In [7,8] it has been proposed the concept of new generation optical switches based on the control elements inside the system. However, it has been only idea, and the problem of the parameter calculation has not been solved in those works.

Here we present the detail description and the numerical calculations of these devices in optical domain (1550nm): the controlled system including Bragg filter, frequency detector, optical isolator,
and former of a control signal. All these devices are based on isotropic and anisotropic inhomogeneous, in particular stratified, structures. To calculate the ones, the analytical methods in scope of linear problem [10,12] are applied in our treatment. Note, that various optical structures have already been calculated by using those mathematical approaches, however here we first of all present practical applications of the developed method and also we obtain unique properties of the structure that allow us to create next-generation all-optical switching cell.

2. The optical switching cell structure
The next-generation 4x4 all optical switching cell containing the buffer device and the switching unit (figure 2) has been presented in [7].

The functional principle of the cell is based on frequency separation of control and information signals. Here an input optical signal consists of two control signals with the wavelength \( \lambda_{c1} \), \( \lambda_{c2} \) and an information signal with the wavelength \( \lambda_i \). The principle of frequency separation is shown in figure 1.

![Figure 1. The structure of input signal.](image)

These signals are separated by the Bragg filter (BF) of the switching unit. In the considered case this Bragg filter is actually an isotropic stratified periodic structure. Thus, control signals with \( \lambda_{c1} \) and \( \lambda_{c2} \) are reflected in the Bragg filter and transmitted to the optical isolator (OI) and an information signal \( \lambda_i \) transmits through the structure to the displacement system (DS). After OI a control signal transmits to the frequency detector (FD). The displacement system is a controlled photonic crystal. Actually it is multilayered structure including ferromagnetic, optoelectronic, thermoelectric or ferroelectric films. The properties of this film can be charged by an external control signal (voltage, current, thermal or optical radiation) and therefore a refractive angle can be controlled by an external signal. We choose the material controlled by an external magnetic field (ferrite-garnet) in our system: It is important that ferrite-garnets are the only existing magnetic controlled materials in the optical domain for today. The frequency detector converts the frequency deviation of the control signal into its amplitude deviation. It also is inhomogeneous isotropic structure with linear dependence of the reflection coefficient on a frequency in the operating domain. Analogous devices in terahertz and optical domains have been described in [13,14]. The amplitude-modulated optical signal from the frequency detector is transmitted to the displacement system (DS) that includes a controlled light emission diode and low frequency control scheme. The operating principle of the displacement system (DS) is described in detail in [15] because we do not represent it here. This system has one input and four outputs. For effective control of cell functioning, it is necessary to use two signals with different values. The combination of these two control signals determinates the necessary output.

It is obvious that the buffer-multiplexing device must be used in this scheme as the DS has four outputs and only one input (figure 2). The buffer device includes the optical integrated device (OIU) and the four controlled delay lines (DL). The optical integrated device contains the optical multiplexer
3. The optical isolator

The optical isolator is designed to transmit control signals in one direction only. The operation principle of the optical isolator is shown in figure 3. The isolator contains a radar, a receiver, and a stratified slab. The main element of this isolator is a stratified anisotropic slab possessing nonreciprocal properties. Non-linear properties of the presented isolator are based on a dependence of the medium properties, in particular reflection and transmission coefficients, on an incident angle and an orientation of an external magnetic field. It is important that such properties don’t appear in the cases of a normal and tangential orientations of a magnetic field.

For today, we can propose the two types of the isolators. The optical isolator shown in figure 3a is functioning as reflected structure and the one functioning based on transmission principle (figure 3b).
Let us consider the first principal (figure 3a). If an incident control signal passes in the direction 1 than the reflection coefficient is about unit and a maximum power propagates to the receiver (the direction 1). The transmission coefficient is about zero in this case. If an incident control signal passes in the direction 2 than the reflection coefficient is equal to zero and a signal propagates through the slab but not propagates to the radar.

Now let us consider the second structure principal (figure 3b). If an incident control signal transmit along the direction 1 than the transmission coefficient is approximately unit and a signal transmits through the slab to the receiver. In the case of incidence from the receiver (direction 2) a signal is totally reflected and it does not transmit to radar.

A very important characteristic of an isolator is its amplitude response. During the researches it has been carried out numerous calculations and it has been chosen the optimal structure [16]. This structure includes the 12 double-layered periods. The first layer is $FeF_2$ and the second one is $MnO$. Here it is taken $f = 1.93 \cdot 10^{14}$ Hz, $\beta = 30^\circ$, $\varphi = 50^\circ$. The dependences of the reflection coefficient on an incidence angle for this structure (the amplitude characteristic) are presented in figure 4.

![Figure 4](image)

**Figure 4.** The dependence of the reflection coefficient on the incidence angle for $f=1.93 \cdot 10^{14}$, $\beta = 30^\circ$, $\varphi = 50^\circ$.

It is seen that the reflection coefficient is minimal ($R=0.05$) at $\alpha = 76.4^\circ$ and the one is unit at $\alpha = -76.4^\circ$ for $\beta = 30^\circ$ (the solid line).

Thus this structure has the isolator properties and it passes a signal only in a forward direction and doesn’t pass a signal in an opposite direction.

![Figure 5](image)

**Figure 5.** Dependence of the reflection coefficient on an incidence angle for difference inclination angles $\beta$ at the frequency $1.93 \cdot 10^{14}$. 
Figure 5 shows the results demonstrating the possibility of mechanical tuning of the isolator by changing the angle of the anisotropy axis inclination. The minimum shifts from $\alpha = 72^\circ$ to $\alpha = 82^\circ$ if inclination angle changes from $\beta = 25^\circ$ to $\beta = 40^\circ$. Simultaneously, the angle bandwidth is narrowed and it is equal to $28^\circ$, $10^\circ$, and $6^\circ$ correspondingly. Decreasing the inclination angle less than $\beta = 25^\circ$ and increasing it more than $\beta = 50^\circ$ leads to disappearance of the angle selective properties of the structure.

4. Optical Frequency Detector

Here we also offer frequency detector based on a 1D anisotropic photonic crystal (stratified anisotropic structure). This demodulator transforms a frequency modulated signal to an amplitude modulated signal. Note that the analogous method has been used in the radio frequency domain. For the demodulation it has been used an ordinary electrical oscillating circuit. The central frequency of a signal, in this case, must correspond to a linear interval of the resonance characteristic (figure 6).

![Figure 6. Principle of transformation of a frequency modulated signal to an amplitude modulated.](image)

**Figure 6.** Principle of transformation of a frequency modulated signal to an amplitude modulated.

![Figure 7. Geometry of the problem: a) a cross-section of a one-dimensional crystal; b) an orientation of the axes within a single layer (\(k_i\) is a wavevector of \(i\)-th eigenwave within a single layer, \(\alpha_{\text{inc}}\) is an incidence angle, \(\theta\) is an inclination angle, \(\varphi\) is an angle between an incidence plane and a plane including an anisotropy axis).](image)

**Figure 7.** Geometry of the problem: a) a cross-section of a one-dimensional crystal; b) an orientation of the axes within a single layer (\(k_i\) is a wavevector of \(i\)-th eigenwave within a single layer, \(\alpha_{\text{inc}}\) is an incidence angle, \(\theta\) is an inclination angle, \(\varphi\) is an angle between an incidence plane and a plane including an anisotropy axis).
To realize the described method we used an anisotropic stratified structure with an arbitrary orientation of the anisotropy axis. The important is the fact that a wave is propagating along a slab ($\alpha_{\text{inc}} = 90^\circ$). The functioning principle of the one is based on the so-called "penetration" effect and a dependence of the reflection coefficient on an anisotropy axis orientation.

For this in this work a dependence of the reflection coefficient on an anisotropy axis orientation is studied for the case of tangential propagation of an incident wave (along the y-axis (figure 7 a)).

Our main aim is studying a dependence of reflection coefficient on an orientation of the anisotropy axis for the case of a tangential wave propagation and investigating practical applications of the obtained results for a tangential wave propagation under a structure ($\alpha_{\text{inc}} = \pm 90^\circ$) for the arbitrary angles $\theta$, $\varphi$ (figure 7b), and finding the practical applications of these properties.

Let us consider a dependence of a reflection coefficient on a frequency for $\alpha_{\text{inc}} = 90^\circ$ presented in figure 8. It is seen that this characteristic is resonant and additionally the one is approximately linear in the resonance domain ($f_0 \pm \Delta f \approx 1.93 \cdot 10^{14} \pm 0.03 \cdot 10^{14} \text{Hz}$). If $f_0 = 1.93 \cdot 10^{14} \text{Hz}$ is a center frequency, then for a frequency deviation $2\Delta f = 0.06 \cdot 10^{14} \text{Hz}$ the reflection coefficient varies in accordance to the law of an input signal in the scope of $R_0 = \pm \Delta R \approx 0.6 \pm 0.3$. Therefore the amplitude of reflected signal varies in accordance to the same law. Thus this structure transforms a frequency modulated signal to an amplitude modulated one. Then an amplitude modulated oscillation can be detected by the well-known approaches.

The considered principle can be used in any frequency domain as choosing parameters of a structure it is possible to obtain an analogous resonance characteristic in any frequency domain.

It is obvious that an analogous device can be created for the case of a normal incident wave and the case of an oblique incidence. In our view dimensions of a device must be smaller in the case of tangential wave propagation.

5. Bragg filters

The Bragg filter is used for separating a control signal and an information signal. The pass interference filters under a normal incident of an electromagnetic wave is studied. The filter is based on a plane-parallel isotropic stratified structure.

The calculation of the main optical parameters for the three structures of multi-layered interference filters is carried out in [17]. The layer thickness is multiple of quarter of the wavelength.

The initial data for the calculation are taken in accordance with [17]: the central wavelength of a filter is from 780nm to 1600nm, type of a filter by spectral characteristic is narrow band pass, bandwidth at the level of 3dB is less than 100nm, level of the assured decay is more than 40dB, a total thickness of a multilayered structure is 0.2–1.5mm. A medium is isotropic, lossless, without frequency dispersion. The geometry of the problem is shown on figure 9.

![Figure 8](image_url)

Figure 8. The illustration of principle of frequency detector; it is studied a slab containing 12 double layered periods for $\theta = 5^\circ; \varphi = 87^\circ$. 

The results of the interference multilayered filters calculation are discussed in this section of the paper. For the calculation the characteristic matrix method [10,12] and the method of the needle variation of the refractive index of the layer’s material of coating [17] are used for obtaining the best kind of an amplitude-frequency characteristic in the passband.

![Figure 9](image)

**Figure 9.** The multilayered optical structure of the filter [9]: $n$ – index of refraction, $d$ – layer thickness, $\theta$ – angle of wave’s incidence.

During a research with the use of [17,18] the three structures of filters are got with the different number of layers and sequence of materials with the different indexes of refraction. So, a filter with a structure 1 $(H34L2(HL)H46L2(HL)H44L2(HL)H34LHG)$ contains of 21 layers, where $H$ – a material with the index of refraction $n = 2.3$ and the thickness is quarter of wave-length, $L$ is a material with the index of refraction $n = 1.38$, $G$ is a base sheet of glass with the index of refraction $n=1.52$. The filter structure 2 $(1.35M1.07L0.7M1.27H2(LH)L4H7(LH)L2H8(LH)H48(LH)H2L8(HL)4H3(LH)LG)$ is obtained by using the method [17,18]. Here $M$ is a material with the refraction index 1.32, $H$ is a material with the greater index of refraction 2.16, the refraction index of $L$ is 1.46, and $G$ is a glass substrate with the refraction index 1.52.

Applying the method [17,18] to the described in that work structure we obtain the resulting filter with the structure 3 containing 82 layers that can be described as: $1,35L 1,3H 2(LH)L4H 7(LH)L2H 8(LH)L4H 8(LH)2H 7(LH)4H3(LH)G$ (structure 3), where $H$ is a material with the refraction index of $n=2.16$, $L$ is a material with the refraction index $n=1.46$, $G$ is the glass substrate with $n=1.52$.

![Figure 10](image)

**Figure 10.** The amplitude-frequency characteristic of the filter (3).

In figure 10 it is shown an amplitude-frequency characteristic of the filter based on the structure (3). This filter (3) is characterized by the followings parameters: half-width is $\delta\lambda_{0.5} = 16.1\text{nm}$, decimal width is $\delta\lambda_{0.1} = 21.8\text{nm}$, slope of characteristic is $\eta = \delta\lambda_{0.1}/\delta\lambda_{0.5} = 1.35$, bandwidth at the level of 1dB is $\Delta\lambda_{1\text{dB}} = 13.3\text{nm}$, bandwidth at the level of 3dB is $\Delta\lambda_{3\text{dB}} = 14.7\text{nm}$, minimum
insertion loss is 0.102 dB, maximum insertion loss is 0.245 dB, ripple of amplitude-frequency characteristic is 0.143 dB, level of the assured fading is 103.54 dB, adjacent channel isolation is 24.7 dB, non-adjacent channel isolation is 65.7 dB, thickness of the stratified slab is 0.206 mm, transmittance in a maximum is $T_{\text{max}} = 97\%$. The filter with a structure (3) has the best characteristics of the calculated ones. It has more even amplitude-frequency characteristic in the pass band, see figure 11. In figure 11 the bandwidths of the obtained filters (1-3) are presented also.

6. Conclusion
In this work the control system of the 4×4 next generation switching cells is presented for the first time. These new cells are all-optical and self-tuning and these cells can be functioning without an external control system. The development of all optical switching elements is an important stage of all optical communication networks transition. The inside controlled system of the cell includes Bragg filter, frequency detector, optical isolator, and former of a control signal. These devices are described in our paper and the calculations of it’s parameters are presented. First, the function principles of these devices are considered and also we obtained the amplitude characteristics of the offered structures in the third transparent window.

![Figure 11. Bandwidths of the got filters: 1) the filter with the structure (1); 2) the filter with the structure (2); 3) the filter with the structure (3).](image)

The optimal structure parameters and reflection and transmission coefficients of the optical isolator are obtained. The reflection coefficient is 0.05 at the incident angle is 76.4° and the one is unit at the incident angle is -76.4°. The optimal parameters and amplitude frequency dependence of the frequency detector are calculated too. We obtained that in the considered case a slab must contain 12 double-layered periods, and it is seen that amplitude frequency dependence is approximately linear in the resonance domain $1.93 \cdot 10^{14} \pm 0.03 \cdot 10^{14}$ Hz. The passband of the Bragg filter is presented, and amplitude characteristic of frequency detector is calculated. We obtained that the bandwidth of the Bragg filter structure at the level of 1dB is $\Delta \lambda_{1\text{dB}} = 13.3$ nm, bandwidth at the level of 3dB is $\Delta \lambda_{3\text{dB}} = 14.7$ nm.

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