High-performance 1×4 - demultiplexer for next-generation all-optical telecommunication systems

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Abstract. In this paper the new 1×4 optical demultiplexer for next-generation all-optical switching systems is proposed. The controlled mirrors are the main elements of this device. The control voltage for this mirror is generated by a rectenna from an optical control signal. In accordance to operation principle this optical signal enters the system simultaneously with an information signal. The analytical approach of calculation energy losses in the demultiplexer based on the translation matrix method is proposed. And also the analytical method of performance calculation is offered for the first time. First of all, the delay time due the transient mode in the power supply circuit is found. The equivalent electrical scheme of the optical demultiplexer is proposed for the first time. Note that the theoretical results obtained in this work can be used for analysing various controlled optical devices. The numerical calculations in accordance to the presented methods are carried out also.

1. Introduction
Developing all-optical switching systems is one of the perspective directions of modern telecommunications. For today it is discriminated the various types of all-optical switches depending on a technology and a method of optical beam control. In modern literature it is distinguished mechanical, electro-optical, thermo-optical switches, optoelectronic switches based on semiconductor optical amplifiers, integrated active-waveguide switches, switches based on photonic crystals, switches based on multilayer liquid crystal matrices, switches on integrated circuits with a set of matrices of optoelectronic isolator [1]. Among these switch types the electro-optical switches are fastest [1–4]. In the some theoretical works it is shown that the switching time of electro-optical switches is hundreds of picoseconds [5, 6]. But in most experimental works performance of electro-optical switches is not more than nanoseconds [2–4, 7–9]. One of the reasons of low speed of one’s is necessity of external control of switching process. To solve this problem the new types of switching systems [10, 11] based on 4×4 and 8×8 all-optical switching cells with decentralize control [12, 13] have been proposed. These are the so-called dual photon systems based on the two important principles. The first principle is based on a combination of time and space division of signals. And the second one is based on parallel transmission of information and control optical bits. These principals determine the main advantages of the dual photon systems, such as non-blocking, low complexity, scalability, and high performance.
At the same time, the development of the element base of all-optical systems is the important big problem. For example lack of real high-speed optical cells is one of difficulty of implementation of all-optical high-speed switching systems. So performance of optical switching cells presented in one of the last papers and based on MEMS technology is only 400 ns [2]. In [4] the low-power non-blocking electro-optical 4×4-switch based on 2×2 Mach–Zehnder interferometer is presented. The experiments have been carried out for wavelength of 1550 nm. Those results showed that the power consumption is less than 20 mW, the crosstalk is less than -9 dB and the switching time is about several nanoseconds. However, there are only two papers where the authors have presented high-speed all-optical cells [11, 12]. The performance of these cells in accordance with calculation results [5] is 1.5·10^12 s. Unfortunately, the spatial displacement of the optical signals in those 1×4- and 1×8-demultiplexers is not sufficient for providing reliable and quality operation.

Thus, there is the problem of developing a new type of optical demultiplexers which can be used in the next generation photon switching systems and provided high speed and necessary spatial displacement of optical signals.

Operation principle of the new 1×4 demultiplexer is described in subsection 3.1. The analytical approach of energy loss calculation based on the translation matrix for the offered demultiplexer type is presented in subsection 3.2 for first time. The calculation method of optical signal delay time in proposed switching element is considered in Subsection 3.3. The numerical calculations are given in section 4. The results of these calculations allowed us to improve the power supply scheme. Moreover the development of mathematical model of such a demultiplexer is the important theoretical problem of this work.

2. Statement of the problem

In [1–4, 6–10] different types of optical switching systems have been considered. The disadvantage of all these switches is insufficiently high performance due to using electron central devices. Unlike them the next generation all-optical switching systems based on the 4×1-multiplexer and 1×4 demultiplexer [10–12] use decentralized control and so their performance is about hundred times higher [5]. However as it is noted above there is the problem of constructing demultiplexer for such the high-speed high-capacity optical system. This problem is insufficient spatial displacement of optical signals. Thus it is required to develop a relatively simple device with low loss, high speed, and low crosstalk.

The aim of this work is development of the new 1×4 optical demultiplexer for the next-generation optical switching system [10–12]. The demultiplexer must provide high performance, low losses, and sufficient optical beam separation in comparison to the well-known schemes [1–4, 6–10]. In this regard the energy characteristics and performance of this device are analysing in the work. Another important objective of the paper is transient time calculation which must be taken into account, since it makes the most significant contribution in switching time.

3. Physical foundations

3.1. Operating principle of the 1×4 demultiplexer

The illustration of proposed demultiplexer is shown in figure 1. This demultiplexer consists of the controlled mirrors (1)–(3), which are the stratified structures with the uncontrolled usual dielectric and controlled lithium niobate layers. It is obvious that the mirrors to be controlled by electrical field. A control voltage is generated by a rectenna from a control optical signal that enters to the system simultaneously with an information signal [10–13]. The control electrodes are located at the end walls of the mirrors. Additionally, the system contains the uncontrolled mirrors (4) and (5), which are silver or gold slabs. The reflection coefficients of these ones are equal to unit.

Now let us consider the operating principle of the proposed device. An optical signal propagates from the input to the controlled mirror (1). The next direction of a signal depends on the control voltage applied to this mirror. If \( U_i = 0 \) an optical signal transmits through the mirror 1 and propagates to the controlled mirror (2). In other case \( U_i = Uc1 \neq 0 \) (figure 2)) a signal is reflected...
by the mirror (1) and it propagates to the controlled mirror (3). Next, the output number depends on the control voltage \( U_2 \) applied to the mirrors (2) and (3). In the first case when the voltage \( U_2 \) is equal to zero an optical signal passes through the mirror (2) and propagates to the first output. In second case it passes through the controlled mirror (3), then it propagates to the mirror (5) and then to the 4-th output. When the voltage value \( U_2 \) corresponds to the unity level (\( U_2 = U_{C2} = U_{C3} \neq 0 \) (figure 2)), an optical signal in the first case is reflected by the mirror (2), then it transmits to the mirror 4 and then to the (2) output, in the second case it is reflected by the mirror (3) and then it transmits to the third output.

One of the important characteristic of an optical device is energy losses. Here these losses are defined by the losses within the host medium \( W_{hm} \), the losses within the mirrors \( W_m \), the losses at the input interface \( W_{in} \), and the losses at the output interface \( W_{out} \) of the demultiplexer. Thus,

\[
W = W_{hm} + W_m + W_{in} + W_{out},
\]

where the value \( W_{hm} \), \( W_m \), \( W_{out} \) can be calculated by using the approaches described in [12] without problem. And the investigation of \( W_{in} \) is the partial important problem, and this problem is solved here analytically.

The demultiplexer performance is determined by the delay time in the host medium \( t_{hm} \), the delay time in the mirrors \( t_m \), and delay time due to the transient mode \( t_p \)

\[
t_{delay} = t_{hm} + n \cdot t_m + t_p,
\]

where \( n \) is the number of the mirrors.

**Figure 1.** Illustration of the 1×4 deflector.

### 3.2. Reflection coefficient calculation

One of most important point in the considered problem is investigation and calculation of the reflection and transmission coefficients of the controlled mirrors.

In this work we used the translation matrix method described in [13, 15] in detail. The method is simplified by the facts that an optical wave is considered as plane and the limited dimensions of the slab are not taken into account. However it demonstrates good agreement with the experimental results [12]. In accordance to the method the reflection coefficient is

\[
R = \frac{(m_{11} + m_{12} \rho_0) \rho_0 - (m_{21} + m_{22} \rho_0)}{(m_{11} + m_{12} \rho_0) \rho_0 + (m_{21} + m_{22} \rho_0)},
\]
and the transmission coefficient is

\[ T = \frac{2\rho_0}{(m_{11} + m_{12}\rho_0)\rho_0 + (m_{21} + m_{22}\rho_0)}, \quad \text{(4)} \]

where \( \rho_0 = \sqrt{\mu_0/\varepsilon_0} \) is the wave impedance of vacuum, \( \mu_0, \varepsilon_0 \) are the permeability and permittivity of vacuum, accordingly, \( m_{ij} \) is the translation matrix element. In accordance [13, 15] the translation matrix of a multilayer structure can be found as

\[ M = \prod_{i=1}^{N} M_i, \quad \text{(5)} \]

where the translation matrix \( M_i \) of \( i \)-th layer

\[ M_i = \begin{pmatrix} \cos \varphi_i & -j \sin \varphi_i \\ j p_i \sin \varphi_i & \cos \varphi_i \end{pmatrix}. \quad \text{(6)} \]

In (6) it is denote \( \varphi_i = k_d n_i d \cos \theta_i, \theta_i \) is the propagation angle within the \( i \)-th layer, \( d_i \) is the thickness of the \( i \)-th layer, \( n_i \) is the reflection index of the \( i \)-th layer, \( k_0 = \omega \sqrt{\varepsilon_0 \mu_0}, \quad p_i = \sqrt{\varepsilon_i / \mu_i} \cos \theta_i \) for TE-wave or \( p_i = \sqrt{\mu_i / \varepsilon_i} \cos \theta_i \) for TM-wave, \( \mu_i \) and \( \varepsilon_i \) are the permeability and the permittivity of the \( i \)-th layer, accordingly.

Note that the modules of (3) and (4) give us parts of the reflected and transmitted fields, and the argument is used for calculation of delay time. The reflection indexes of usual dielectric layers are determined by permittivity and permeability. And if we consider a controlled layer based on lithium niobate than the reflection index is defined as [13]

\[ n = n_0 - \frac{r n_0^3}{2d} U - \frac{\zeta n_0^3}{2d^2} U^2, \quad \text{(7)} \]

where \( n_0 = \sqrt{\varepsilon}, \varepsilon \) is the permittivity of the lithium niobate layer, \( r = 10^{-11} \) is the Pockels coefficient, \( \zeta = 10^{-14} \) is the Kerr coefficient, \( d \) is the width of a layer, \( U \) is a voltage applied to a layer.

3.3. Delay time calculation

As it is noted above the performance of the demultiplexer is determined by the delay time of a signal due propagation within host medium and the controlled mirrors, the time of the transient mode when changing the capacities of the controlled mirrors.

The time delay in host material can be defined as

\[ t_{\text{hm}} = \frac{L}{v_{\text{hm}}}, \quad \text{(8)} \]

where \( L \) is the path length, \( v_{\text{hm}} \) is the speed in the host materials. For first outputs (figure 1) we have

\[ L_{x1} = L_0 + L_4 + L_5, \text{ for the second output } L_{x2} = L_0 + L_4 + L_6, \text{ for the third output } L_{x3} = L_0 + L_5 + L_7, \text{ for the fourth output } L_{x4} = L_0 + L_4 + L_5 + L_8. \]

The time delay in a mirror is defined by the transmit time of a wave in the mirror and the phase shift at the interfaces of a mirror.
if we consider reflected signal, and
\[ t_m = \frac{L}{v_m} + \arctan \left( \varphi_r \right), \]  \hfill (10)

if we consider transmitted signal. Here \( \varphi_R = \arg R \), \( \varphi_T = \arg T \). As it is seen from figure 1 and the expressions (8)–(10) the delay times for different outputs are different.

Moreover, each controlled multilayered mirror can be considered as a capacitor. The delay time must also be defined by the change accumulation time of these capacitors. From this point of view power supply circuit of mirrors can be presented as the equivalent electrical circuit (figure 2). Here \( E_1 \) and \( E_2 \) are the power supply electromotive forces, \( R_1 \) and \( R_2 \) are the power supply resistances, \( R_1 \) and \( R_2 \) are the resistances of the common power wires of the first mirror, and second/third mirrors, correspondingly, \( L_1 \) and \( L_2 \) are inductances of the power wires of the first mirror, and second/third mirrors, correspondingly, \( R_{11} \) and \( R_{22} \) are the resistances of the wires of the second and third mirrors, correspondingly, \( L_{11} \) and \( L_{22} \) are the inductances of the wires of the second and third mirrors, correspondingly, \( C_1 \), \( C_2 \), and \( C_3 \) are the capacitances of the first, second, and third mirrors, correspondingly, \( R_{1l} \), \( R_{2l} \), and \( R_{3l} \) are the leakage resistances of the first, second and third mirrors, correspondingly, \( K_1 \) and \( K_2 \) are the keys connecting voltages \( U_1 \) and \( U_2 \).

Let us consider the case when the key \( K_1 \) closes the circuit, and the key \( K_2 \) doesn’t close the circuit. Taking into account figure 2 we can write the different equation
\[
\frac{d^2 U_{c1}}{dt^2} + \frac{C R_{11} R_{21} + C R_{12} R_{22} + L_1}{R_1 L_1 C_1} \frac{d U_{c1}}{dt} + \frac{R_1 + R_1 + R_{l1}}{R_{l1} L_{c1}} U_{c1} = E_1
\]  \hfill (11)

That allows us to find the voltage \( U_{c1}(t) \) across the capacitor \( C_1 \). The solution of this equation is
\[
U_{c1} = \sum_{i=1}^{2} A_i \exp \left( p_i t \right) + U_{c1l},
\]  \hfill (12)

where the constants \( A_i \) are defined by the initial conditions, \( p_i \) are the roots of the characteristic equation of (11), \( U_{c1l} \) is the voltage in the steady-state mode that occurs after the switching one.

![Figure 2. The equivalent electrical circuit.](image)

In the case when the key \( K_2 \) closes the circuit, and the key \( K_1 \) doesn’t close the circuit the differential equation system can be written in the form
The solution of (13) must be written in the form

\[
U_{c2} = \sum_{i=1}^{3} B_i \exp(p_i t) + U_{c2s}, \\
U_{c3} = \sum_{i=4}^{6} D_i \exp(p_i t) + U_{c3s},
\]

where \( B_i \), \( D_i \) are defined by the initial conditions, \( p_i \) are the roots of the characteristic equation of (13), \( U_{c2s} \), \( U_{c3s} \) are the voltages in the steady-state mode that occurs after the switching one.

Analogously the transition mode when the keys \( K1 \) and \( K2 \) close the circuits simultaneously can be described. Now the transient time can be calculated as \([5, 17] \, t_p = (3 \div 5)/p_{\text{min}}\), where \( p_{\text{min}} \) is lowest characteristic exponent of (11) and (13).

4. Numerical calculations

In this section the particular optical structure that used as the 1×4-demultiplexer is considered, the dependences of the reflection and transmission coefficients on the control voltage and delay time of a signal within the device are calculated. Here the controlled mirrors are chosen as double-period stratified structure containing the lithium niobate nanofilm and the two dielectric layers with the reflection indexes \( n_2 = 3.6, \, n_3 = 6.0402 \) and thickness \( d_2 = 2 \cdot 10^{-6} \text{ m}, \, d_1 = 1 \cdot 10^{-3} \text{ m} \). Taking into account the information of literature sources [16] and the result of plenty numerical experiments it is chosen \( n_h = \sqrt{r} = 2.7, \, r = 10^{-11}, \, \varepsilon = 10^{-14}, \, d = 2 \cdot 10^{-9} \text{ m} \) for lithium niobate film. Note that in the presented calculations we neglect the finite dimensions of the device elements. The host material in the calculations is described by \( \varepsilon_h = 1.1, \, \mu_h = 1 \).

4.1. The reflection and transmission coefficients

Here the dependence of power reflection coefficient on the wavelength and applied voltage is studied. The results of the numerical calculations are presented in figure 3 for the material parameters written above, the incidence angle is \( \theta_0 = 45^\circ \). Figure 3(a) shows the dependence of the reflection coefficient on the voltage and permittivity, figure 3(b) shows the dependence of this coefficient on the voltage and wavelength.

As it can be seen (figure 3), the considered structure is actually an electro-optical switch at \( n_2 = 6.0402 \) and \( \lambda = 1550 \text{ nm} \). Moreover, switching from one state to another requires voltage change from 0V to 0.1V. The reflection coefficient in this case increases from zero to unit for any wavelength within the operation domain. However this structure is narrowband and it properties is strongly dependent on the layer properties.
4.2. The delay time calculations

The delay time is defined by the various factors described above. In this subsection we present the numerical results only for the delay time defined by the transient process in the circuit of the first mirror as in our point of view it is most difficult part of analysis. The equivalent electrical scheme of the studied circuit is shown in figure 4(a). The results for second and third mirrors are analogous, and using the formulas (8)–(10) doesn’t cause problems.

Figure 3. The dependence of the reflection coefficient on the wavelength and the voltage.

Figure 4. The electrical circuit of the demultiplexer.

First of all the important parameters that determinates performance of the considered device are capacities of the controlled mirrors. Note that these capacities are depended on the applied control voltage in the considered case. It also is necessary to take into account the fact that the resulting capacity of the multilayered structure can be found as

\[ \frac{1}{C} = \sum_{i=1}^{N} \frac{1}{C_i}, \]  

(16)

here \( C_i = e_0 \varepsilon_i S_i / d_i \) is the capacity of \( i \)-th layer. The numerical calculations give us the capacity of the controlled mirror \( C_1 = 0.6978 \times 10^{-12} \) F for the mirror square 1 mm\(^2\) and voltage 0.02 V. The inductance of the silver wire can be calculated as \( L = (\mu_0 / 2\pi) \left[ \mu_0 \ln(l/r) + \mu_0 / 4 \right] \) [17, 18]. For the wire length 5.8 mm and the wire radius 0.5 mm we have \( L = 2.16 \times 10^{-9} \) H. The power wire resistance is \( R = \rho l / S_w = 0.9978 \) ohm. The power supply resistance is taken 100 ohm, the leakage resistance is 1 Mohm. The result of the numerical calculations for the first mirror is presented in figure 5(a). As we can see the calculated transient time is 10 \( \mu \)s. Obviously that this result is the very bad. To increase performance it is necessary to change the power supply scheme.
**Figure 5.** The dependence of the voltage on the controlled mirror on time.

**Figure 6.** The power supply scheme of the fast 1×4 demultiplexer.

**Figure 7.** The dependence of the voltage on the controlled mirror on time.
First of all it must be reduced the capacity of the mirror and the resistance of the scheme. For this purpose the additional capacitor \( C_{ad} \) is connected in series with the controlled mirror, and the shunt resistor \( R_{sh} \) is connected in parallel with the power supply circuit (figure 6(a)). Then the equivalent electrical scheme for this case is shown in figure 4(b). The calculation result of such the scheme is presented in figure 5(b). The resulting capacitance and resistance in this case are reduced by a factor 100. Now the transient time is 0.7 ns.

Note that there is another way to reduce the transient time. Indeed the electrical contacts can be connected to the side walls of the mirrors. In this case the capacity is equal to \( 1.6 \times 10^{-14} \) F, and the dependence of the voltage applied to the mirror on time is presented in figure 7(a). The transient time is \( 1.3 \times 10^{-10} \) s in this case. This result is also not good enough. Moreover, the voltage surges are observed for such the circuit parameters.

To improve the demultiplexer characteristics in the transient mode, we propose the power supply circuit shown in figure 6(b). As the result the decrease in capacitance in two times and increase in resistance in 10 times by using the scheme presented in figure 6(b) give us decrease in the transient time to \( 10^{-11} \) s (figure 7(b)).

5. Conclusions
In this paper the optical demultiplexer for the next-generation all-optical switching systems [10–12] is proposed and studied by authors for the first time. This scheme allows to increase the spatial diversity of optical signals in all-optical switching systems. Note that the operation principle of the proposed optical demultiplexer is based on the simple phenomena of reflection and transmission of an optical beam. And the main element of this device is the controlled mirror based on the multilayered structure that includes the lithium niobate nanofilms. The reflection and transmission coefficients are calculated by using the translation matrix method.

The numerical calculations have been shown that the multilayered structure with lithium niobate can be used as a high-performance optical key.

The performance problem of the proposed device is considered also for the first time. To calculate the optical signal delay time of the proposed 1×4-demultiplexer the equivalent electrical circuit of this element has been presented. For this purpose, the accurate analytical method has been proposed. The numerical calculations have been shown that the speed of such the circuit is about \( 10^{-11} \) s which is higher than the speed of existing all-optical elements in 10–100 times.

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