

An Optical Integrated system for Implementation of $N \times M$ Optical Cross-connect, Beam Splitter, Mux/demux and Combiner

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Summary

Two-dimensional ($N \times M$) optical system based on electro-optically encoded superimposed gratings with constant geometry, modular structure and soft control is presented. Our proposed structure can realize many interesting functional blocks with important transfer functions such as cross-connect switching, beam splitting, multiplexing (demultiplexing) and combining of optical signals from N incident (with similar or different central wavelengths) to M output channels for general optical engineering purposes, optical networking and as well as DWDM applications. In this structure tilted superimposed gratings for easily separating the incident and reflected signals are used. Using electrical control pins, totally and partially transmission (or reflection) coefficient (transfer function) is controlled. In this design each incident channel have $2K+1$ individual wavelengths (practically infinite and really depend on encoding methods), which can be redirected to M output channels according to predefined flexible algorithms. The proposed system can be implemented with 3-layers optical waveguide structure including electro-optic core using planar technology with similar or dissimilar modules (Gratings).

Key words:

Electro-optical Integrated circuits and systems, Optical Switching, Mux/Demux, Beam splitter, Combiner, Modular structure

1. Introduction

A huge growth in information traffic, introduced by the explosions in high speed data communication, internet access, high performance parallel computers and mobile as well as by the emergence of multi-media services has triggered an enormous increase in the bandwidth requirements for metropolitan and long haul transport networks.

Most long haul inter-exchange carriers have used dense wavelength division multiplexing (DWDM) as the technology of choice to meet this rapidly growing bandwidth demand. The major reasons for selecting DWDM are its compatibility with the existing fiber optic infrastructure and its cost-effectiveness compared with more conventional approaches. DWDM offers the potential for an enormous transmission capacity by capitalizing on the very large bandwidth of present optical fibers. As an example for these huge bandwidths requirement, there are some applications and products with throughputs of 1.6 Tbits/Sec on a single fiber (160 channels at 10Gbit/Sec) [1]. Currently, in most of these applications the switching is exclusively electronic. Even in optical communications systems the optical signal is first converted to an electrical signal that is switched electronically and then converted back to an optical signal. Electronic switches, however, are already reaching their inherent limits. It is evident that it will not be possible to meet the demands of the emerging broadband communications applications with existing electronic switching technology. Optical implementation of cross-connect switching are expected to possess several inherent advantageous over their electronic counterparts. Also, however, the deployment of DWDM in optical networking has been primarily restricted to point-to-point links, with active reconfiguration and bandwidth management performed at the synchronous optical network/synchronous digital hierarchy layer. As the number of optical channels carried on a single fiber has increased, it has become necessary to manage and restore these optical channels more cost-effectively. This has pushed vendors into the expanding technology area

of the optical and photonic switch. Also, the wide adoption of DWDM in the backbone network is not only providing the required capacity expansion, but is also driving network evolution towards the next generation infrastructure, known as photonic layer, a single multi-service network designed to handle growth, limit overlay networks, and improve bandwidth efficiency. Furthermore, the photonic layer will make it possible to implement a new class of end-to-end wavelength services for customers who want complete flexibility for their high bandwidth data needs. Optical cross-connects are expected to be the corner-stone of the photonic layer providing carriers with more flexible options for building network topologies with enhanced survivability. The main function of optical cross-connects will be dynamically to reconfigure the network, at the wavelength level, either for restoration purposes or to accommodate changes in bandwidth demand.

For implementation of optical cross-connect, there are many reported results. Some researches are based on star coupler and presented for implementation of optical cross-connect switching [2]. Typically in this method, the incoming signals are used to modulate separate lasers of different but fixed wavelengths. The optical signals are then combined in a star coupled, which broadcasts the combined signals to each of its outputs. Switching is accomplished by having tunable receivers at the outputs, whereby each output receiver can tune to any input of its choice. An important optical component in frequency division multiplexing (FDM) switch is the star coupler. A $N \times N$ star coupler can be constructed, in principle, with \log_2^N stages of 2×2 couplers. This type of realization of optical cross-connect has problem for realization of large N. It needs N fixed but different laser sources. Also, it needs tunable outputs, which is another additional conditions. All of these requirements creates complicated situation and are very hard for implementation. Also, this type of realization really used hybrid model and reconfiguration is impossible or is very hard. However, for adding one or more incident channels, one needs to redesign, which is unacceptable from popular system design based on modular structure.

The other published results are related to different combination of free space optical cross-connects with or without using electroholography [3]. In this work, with applying electric potential on holograms based on photorefractive crystals, the previous generated pattern is reconstructed. This method can be used for redirection of light propagating through these crystals. As it is clear, this method has many

errors and problems. One of these problems is nonlinear operation (quadratic electro-optic effect) of electrically controlled holograms, which is very bad for signal routing and redirecting. Another problem is writing process and inability for reconfiguration using single photorefractive crystal. Also, possibility for erasing due to background light including UV and other components is another problem. Finally, this method operates only for redirecting and other functions such as beam Splitter, Mux/demux and etc can't be realized.

Also, there is another research field, which try to realize optical cross-connect switches with capability for realization of high input-output ports using Micro Opto Electromechanical Systems (MOEMS). In this field similar to free space case, switching is performed using moveable micro mirrors, which is controlled with applied potential [4,5]. This method is very interesting for realizing large number of input-output ports. But, in this method realizing of all lenses, mirrors and other mechanical systems are needed more precise control and alignment. Also, the switching time because of mechanical parts is very large approximately millisecond in the best case.

So, based on reviewed researches, there isn't a suitable building block for realization of optical cross-connect switch, Mux/demux, beam splitter and combiner simultaneously on a single chip with acceptable characteristic from switching time, crosstalk and other interesting parameters point of views. Based on our developed idea about encoding superimposed gratings [6] and optical chip including reasonable pin-outs with electro-optical Pockels effect proposed in [7], here, an electro-optical integrated building block with reconfiguration capability using applied potential and modular structure for expanding purpose in the optical integrated circuits form is introduced. Our design has fixed tilted Bragg Grating geometry for separation of incident and reflected components [8], which it is designed by using the encoded superimposing of many gratings depends on individual sub-channels in incident channels with similar or dissimilar central wavelengths. In this case, with applying suitable potential signal, we define module operation. Based on our proposed method the switching time for Cross-connect switching operation with 20×20 input output ports is smaller than nanosecond, which is very good compared MOEMS and other similar techniques. Our method, really, is a 3-layers optical slab waveguide with tilted similar or different metallic strips coating on top layer selectively. This is easy and practical for implementation using single mask and doesn't need alignments. For

incident channels with different central wavelengths, it is enough that in the masking level each row should have different periods for coating metallic strips only. So, our proposed method can be a suitable integrated solution for realization of optical cross-connects as well as other interesting transfer functions.

The proposed method is analyzed in the following sections. In section II, the proposed method is investigated from system structure point of view. Also, applications are presented in section III.

2. System Structure

Fig. 1 shows a basic block for implementation of optical system with capability for realization of optical cross-connect switch, Mux/demux and many other interesting transfer functions. In this block, there are $2K+1$ individual incident wavelengths (practically infinite and depends on encoding method [8]). These wavelengths are applying on the proposed block. Depend on applied control pins some of these incident wavelengths are diffracted to system output with defined format and others are transmitted directly. Applied control signals will control the reflection, transmission, bandwidth and many other interesting quantities corresponding to each individual incident wavelength separately. Electro-optical methods for applying these controls and encoded superimposed algorithms for design of this block are used [7,8]. Efficient reduction of the number of metallic strips and control pins was discussed in [8]. But, it is sufficient to say that using only 200 control pins and electro-optic medium with 3.6 mm length and near to 1mm width we can obtain all important proposed transfer functions. Also, the tilted gratings are used for controlling the diffracted light direction.

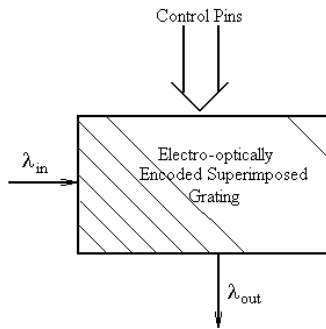


Fig. 1 Basic block for controlling diffracted wavelengths from incident wavelengths

Typical simulations for the proposed building block based on Transfer Matrix Method (TMM) are shown in Figs. 2, 3. Fig. 2 shows completely

reflection of selective wavelengths for DWDM system and Fig. 3 shows selective complete and partial (splitting) reflections. Both of these simulations show our proposed basic block capability.

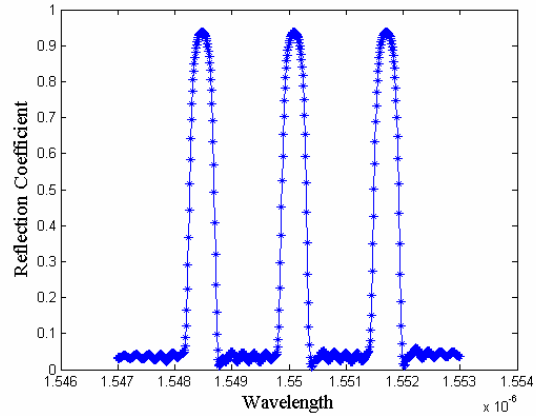


Fig. 2 Completely Reflection for selective incident wavelengths for DWDM system

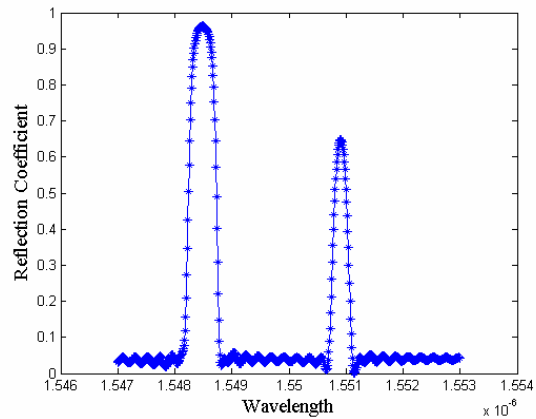


Fig. 3 Completely and Partially Reflection of selective incident wavelengths

As it is shown in Figs. (2, 3), the proposed basic block can be used for implementation of optical systems for realization of many interesting transfer functions.

In this block, the output signal in presence of applied potential (V) can be explained as

$$R_{Out}(\lambda, V) = \sum_{m=-K}^K \zeta(m)R(\lambda - \lambda_m), \quad (1)$$

where $R(\lambda - \lambda_m)$ and $\zeta(m)$ are the reflection profile for standard Bragg Grating centered at

λ_m with specific number of layers and index of refraction induced by applied potential and expansion coefficient related to system parameters and superimposed gratings, which these coefficients are used in the proposed basic block for implementation of superimposed gratings. Since we have used encoding method for realization of superimposing of $2K+1$ wavelengths with constant geometry of Grating, so, $\zeta(m)$ should only depend on samples with position dependency as $\sin(K_m X)$ [7]. But, because of errors in sampling, apodization and other error sources in manufacturing and also, in absence of applied samples because of metallic layers, there are nonequivalent coefficients ($\zeta(m)$) and even in absence of applied potential they have very small but nonzero values. Then, in this situation, the output signal really is weighted superposition of all incident wavelengths. Our calculation and simulation shows that maximum difference between these coefficients for satisfying DWDM demands specifications is less than 0.02 within whole band. So, using this data, we can approximate these coefficients with ideal case. Ideally we have the following relation.

$$V \rightarrow V(\lambda_Q, \lambda_P, \lambda_G) : \text{Then } \zeta(m) = \begin{cases} 1 & \text{for} \\ 0 & \end{cases} \quad (2)$$

$$\begin{cases} m = Q, P, G \\ m \neq Q, P, G \end{cases}$$

In practice, satisfying Eq. (2) is very hard and we should accept some deviation from these ideal coefficients. This subject will introduce crosstalk and other interference effects. So, in this conditions output channels will have nonzero minimum signal level that is increased with increasing crosstalk. For removing introduced crosstalk, suitable apodization can be applied. Fig. 4 shows a proposal for arranging $N \times M$ optical building block, which is introduced in Fig. 1. Of course we should pointed out that this system can be implemented using integrated techniques or in the hybrid form. In hybrid case, each building block should have input and output coupling connectors for decreasing insertion loss. Generally, Fig. 4 shows $N \times M$ matrix arrangement for operating as cross-connect and other proposed transfer functions. In this structure, we assume that there are N incident channels with $2K+1$ individual wavelengths and M output channels.

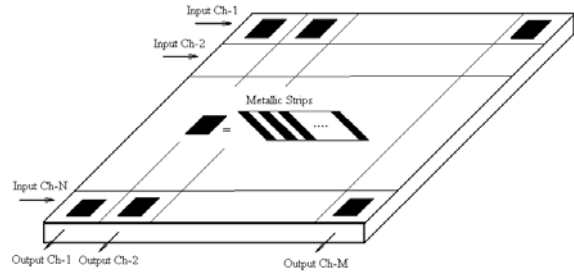


Fig. 4 Schematic of Proposed optical system (Hybrid and Integrated)

For this structure, $N \times M$ basic blocks are used. Each block has control pins separately (C-ij). In the integrated case, Fig. 5 shows some details for waveguiding and limiting to special regions and tapered waveguides in the output for introducing low insertion losses.

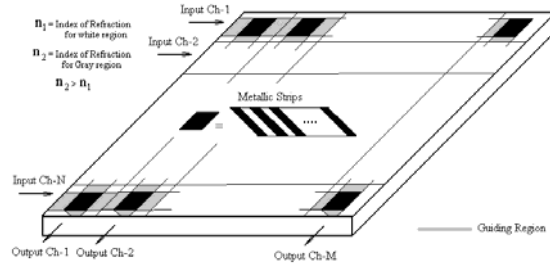


Fig. 5 Detail of integrated assembling of building blocks

As it is illustrated in Fig. 3, with adding guiding regions the interference effects between unnecessary signals is reduced. Also, using tapered waveguides in the outputs the insertion efficiency can be increased. In the next section, we explain important applications related to proposed structure.

3. Applications

In this section, we will review relevant interesting applications, which can be implemented using the proposed optical system.

a) Optical Cross-connect

In this application each wavelength or a group of wavelengths from each incident channels to each output channels should be redirected. Also, maybe there are many redirections, which should be performed simultaneously. For explanation of this application, operation of the proposed system is explained as follows.

For example, imagine that we like redirecting the incident channel m to output channel n totally (or partially) including one wavelength or a group of wavelengths. For realization of this purpose, it is

enough that the control signals should be applied on element (m, n) with suitable algorithm depend on single wavelength or a group of wavelengths [7,8] and the others remain without excitation $((m, j)$ for all $j \neq n$ and (j, n) for all $j \neq m$). With this selection of applied control signals, the incident wavelength (wavelengths) directly transmitted from element $(m, 1)$ to right without perturbation until (m, n) . At element (m, n) depends on applied control pins some of wavelengths redirected to $(m+1, n)$ and directly propagated to the output port at (N, n) . If we need to redirect some group of wavelengths from one incident channel to many output channels without overlapping, this is easy and using explained algorithm it can be implemented. If we like couple simultaneously many wavelengths from different incident channels to different output channels, we should perform as follows. Because of non-overlapping nature, this purpose can be realized easily with applying suitable control pins on suitable elements only. So, based on this explanation, all cross-connect operations can be realized easily with the proposed optical system. Fig. 6 shows cross-connect operation for connection of λ_i component from incident channel j to output channel m . As it is explained, suitable potential for reflection of λ_i component applied on element (j, m) and this operation can be performed. For this structure after applying control potential and because of very fast nature of electro-optic Pockels effect the switching time can be calculated as follows.

$$\tau \leq \left(\frac{n_0[(N+1)l + Mw]}{c} \right), \quad (3)$$

where N, M, l, w and c are number of row, number of column, length of basic block, width of basic block and the velocity of light in free space. As an example, you consider the following data and calculated switching time. Using the following data the switching time can be calculated and is equal to 0.25nsec

$(n_0 = 1.5, N = 10, M = 10, l = 3.6mm, w = 1mm, c = 3 \times 10^8 m/s)$.

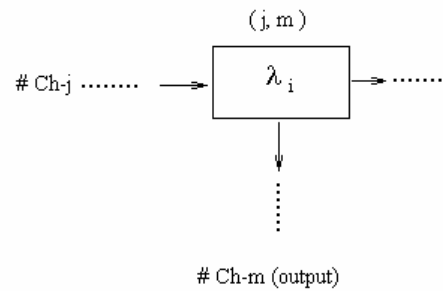


Fig. 6 Cross-connect operation using proposed system

b) Beam Splitter

Using the proposed structure, we can implement splitting operation. In this case, we like redirect single wavelength or a group of wavelengths from one incident channel to more than one output channels according to predefined transmissions ratio. Depends on how many output channels are considered, the applied control pins can be determined using splitting ratios. So, after applying these control pins on desired elements, we can couple the incident wavelengths partially to the output channels. So, the redirected wavelengths simultaneously can be detected on specified output channels. Fig. 7 shows one stage of beam splitting for $\eta\%$ redirection of single wavelength to specified output. For this application there are two methods for implementation using basic block.

1. Changing the index of refraction in whole grating (all length of basic block) for obtaining $\eta\%$ reflection.
2. Applying zero potential to some control pins for converting some part of grating to homogeneous media for obtaining $\eta\%$ reflection.

Each of these methods can be realized using proposed optical system. Of course this operation can be performed with multiplexing and demultiplexing operations simultaneously, which will be explained in the following items. Also, beam splitting can be applied on multi wavelengths with different ratios using single basic block.

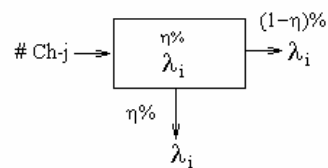


Fig. 7 Beam-splitting operation using proposed system

c) Demultiplexing

Demultiplexing is one of important operations in optical networking. For this operation, wavelengths in one incident channel should be redirected to different specified output channels. For this purpose, we should apply control signals only for one wavelength reflection for each element in the same row corresponding to the incident channel and specified columns. So, based on this explanation, the proposed system redirects each wavelength from single incident channel to each specified output channel. Fig. 8 shows this operation for redirecting first wavelength to first output, second wavelength to the second output and etc. Also, in wavelength redirecting the reflection coefficient can be controlled for beam splitting purpose.

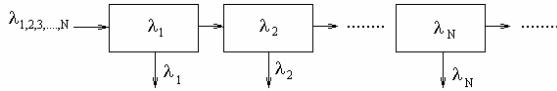


Fig. 8 Demultiplexing operation using proposed optical system

d) Multiplexing

For this application, single wavelength from each incident channel to only one output channel should be redirected simultaneously. So, we should apply the control pins appropriately on specific elements with considering given wavelength for each channel. In this case, special and defined wavelength from each incident channel can be redirected to the desired output channel and this is optical multiplexing. Fig. 9 shows clearly mechanism of optical multiplexing using our proposed system.

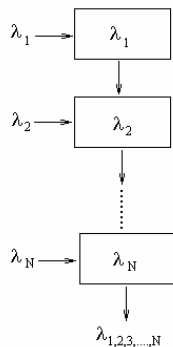


Fig. 9 Multiplexing operation using proposed optical system

In this operation each wavelength can be redirected to output with predefined amplitude using applied

potential for controlling the index of refraction in basic block.

e) Combiner

For this work, single incident individual wavelength from predefined different incident channels should be superposed and transmitted to single output channel. In this case, we should apply special control pins corresponding to partially reflection to desired elements. So, the output channel will have superposition of desired wavelength from incident channels. Fig. 10 shows our idea for combiner operation based on proposed optical system.

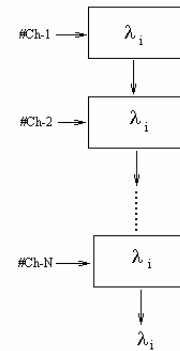


Fig. 10 Combiner operation using proposed optical system

4. Conclusion

In this paper, an electro-optical integrated system using 3-layers waveguide including $N \times M$ basic blocks defined in section II presented for implementation of many interesting optical engineering operations including cross-connect switch, beam splitter, Mux/demux, and combiner. We shown that using appropriate potential applied by control pins all of these operations can be obtained. This optical system is really analog programmable building block for analog optical computation and communication applications. Our proposed cross-connect switch for 10×10 case has smaller than nanosecond switching time.

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