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S 9-3. Optical Performance of Non-blocking 4x4 Optical Switch: Simulation and Experiment

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Abstract: A prototype of pure non-blocking 4x4 optical LC switch was designed and built. This switch is based on conventional LCD technology, where the each pixel controlled the polarization state of the light beam. An addressing algorithm was described. The optical performance of the switch, such as cross-talk and insertion loss, was simulated and experimentally studied. The suggested approach offers several advantages over the conventional cross-point architecture such as: cost; complexity; size; adjustment; and optical performance.

Key Words: Fiber-optic communications, Optical switching, Liquid Crystals, Electro-optics.

1 Introduction

At present, more and more communication transmission infrastructures are based on optical fiber links with practically unlimited bandwidth. The core part of any optical fiber network is an optical switch that allows to route signals between different terminals. Ideally the optical switch should not limit the bandwidth delivered by optical fibers, therefore the switching must be in optical domains avoiding optical-electrical-optical (OEO) conversion. Such (photonic) switches have a fixed cost per port regardless of the amount of bandwidth through each port (or wavelength in WDM systems), because they switch light, i.e. they are bit-rate independent. For this reason, at very high bandwidths, the cost of photonic switching is very attractive compared to OEO (or opaque) switches. Since the bandwidth per port is virtually unlimited by today's standards, a single switch can allow scalability into the hundreds of terabits per second, allowing extremely high nodal scalability. Therefore optical switching networks are fundamental to implementation of future broad-band communication systems.

Many of optical switching architectures are simply optical analogues of electrical or electronic switching networks [1] and do not exploit the additional degrees of freedom (either advantages or disadvantages) provided by the light nature.

Currently the optical switching is performed by Micro Electro–Mechanical Switches (MEMS), which are based on mechanical movements of tiny mirrors. This limits the switching speed and lifetime of such optical switches.

There are also a number of other non-mechanical photonic switching technologies, including: Thermo-optics (e.g., bubble) technology, Surface Acoustic Waves (SAW), Liquid Crystal switching [2,3], etc., allowing to switch an optical routs with rather low cross-talk.

For practical applications the single (binary) optical switches are usually placed in the cross-points of N x N matrix. Such "cross-point" architecture offers simple control and wide-sense non-blocking switching which allows routing of any input to any unused output without disturbing other connections. Unfortunately these approaches are totally impractical due to the large number of cross-points and interconnects required.

On the other hand, the photonic switches must also provide low cross-talk and insertion loss. In cross-point architectures, each output accumulates cross-talks and insertion loss from other N-1 channels, therefore the total matrix switch performance will be unacceptable.

The main drawbacks of the cross-point architecture were finally recognized and several attempts were made to use full advantages of the optical principles [4-5]. For example, use of matrix switch (e.g. LC based multi-pixel SLM) instead of single binary (1 x 2 or 2 x 2) switches is equivalent to relay with many broadband changeover contacts.

Recently we have suggested and patented new approach for LC based multi-channel matrix optical switch. The main idea of this scheme is a use of conventional LCD technology to perform parallel switching in all optical channels. A detailed description of LCD based matrix optical switch was published before [6] therefore here we give a brief description in relation to switch's cross-talk and insertion loss.

The core element of the proposed scheme is TN LC cell in conjunction with lateral displacement beamsplitter (LBS) as shown in the Figure 1a. When the voltage is applied to LC pixel the vertically polarized light beam passes through the LC layer (pixel) without changing the direction of polarization– this corresponds to "bypass" state. When there is no voltage on the pixel, the pixel is in twisted nematic (TN) state and rotates the polarization by 90° to perform lateral displacement. Therefore such switch performs simple 1-to-2 binary switching.

2 Basic Matrix Switch

The architecture and construction of proposed matrix switch in simplest (basic) 4 x 4 port configuration is shown in the Figure 2a. The matrix optical switch can be assembled by simple stacking two Switching Arrays (SA), where the first of them performs horizontal (right) shift on 2-pixel distance and the second one – vertical (up) shift; four square-shaped collector lenses and four output fibers.

LC based Spatial Light Modulator (SLM) consists of 16 (4x4) pixels which are arranged in square fashion in four 4-pixels groups (Fig. 2b). Each pixel has 4-digit code (index):

klmn where *kl* defines the index of the group and *mn* defines the index within each group.
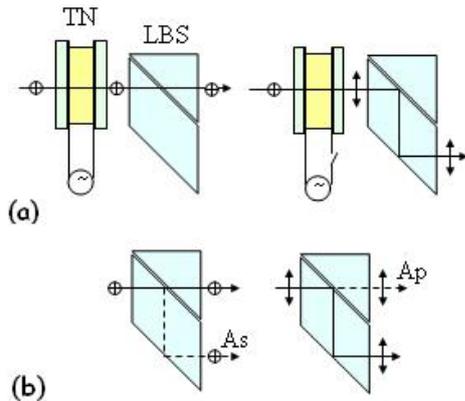

Figure 1 Schematic diagram of binary optical switch based on TN cell and ideal LBS (a) and cross-talk sources in real LBS (b).

All the input channels are coming to the first (*kl*=00) group and the index of channel is a binary number of *mn* (e.g. *2m* + *n*). The output channels collect all traces from the proper groups and the index of output channel is a binary number of *kl* (e.g. *2k+l*). In basic switch architecture only bottom half of SLM will be actually used as shown in the Fig.2a.
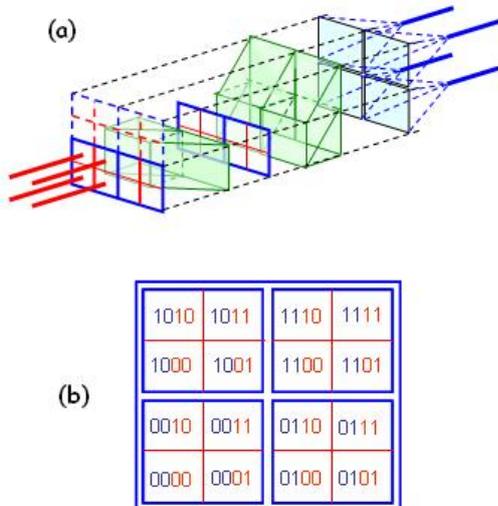

Figure 2 Spatial distribution (a) of input optical routs and total construction (b) of 4 x 4 matrix switch.

Such indexing provides simple routing algorithm e.g. *k≠m* is a condition for horizontal switching and *l≠m* - for vertical switching. Horizontal switching (shift) occurs when the light polarization is vertical (+) and vertical switching – for horizontal polarization (↕).

Such architecture provides strictly non-blocking switching and also several additional features, e.g. several (or even all) the input beams can be sent the same output (ADD function) or one input beam can be sent (splitted) to several (or even all, see Fig.3a) output channels.

The architecture of larger optical switches is similar to the described 4 x 4 switch (N=4, n=2) with only one important

difference– it needs extra pair of beamsplitters with different (double) lateral displacement. For example, let's consider larger 16 x 16 optical switch (N=16, n=4 and N=n^2). In this case the SLM consists of 126 (8 x 16) pixels and 4 switching stages [1].

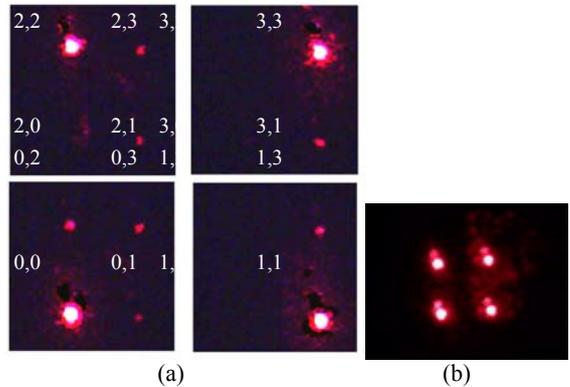Similarly, 64 x 64 optical switch (N=64, n=8) consists of 2048 (32 x 64) pixels SLMs and 6 switching stages.

Figure 3. Input beam can be sent to any of four outputs (a) or to all four output channels (b).

3 Cross-talk of Binary Switch

In the proposed binary switch configuration there are two independent sources of parasitic light: one is due to limited contrast ratio of LBS and another due to non-perfect polarization rotation in TN structure.

First consider the cross-talk from LBS (Fig. 1b). Ideally, the vertically polarized beam must totally pass the LSB straightforward, but practically some part of the light is reflected from air split and shifted by LBS as shown in the Fig. 1b. Let's denote the attenuation of this part as As. Similar is for the horizontally polarized light, where the part of light (Ap) passes straightforward through the LBS. For the LBS used in the prototype, these values are found as As ~ 19 dB and Ap ~ 27 dB.

The cross-talk sources from LC can be also characterized by two independent attenuation parameters: A1 due to depolarization of the light passing through the switched pixel and A0 characterizing how closely the light rotates on 90 degrees when passing through the TN structure. A0 is in fact shows how closely TN structure satisfies to the (second) Mauguine minimum [7]. This depends on a number of parameters such as wavelength, refractive index, the cell thickness and its tolerance. For SLMs used in the prototype with the thickness of 5.9 ±0.15 μm the theoretically achievable attenuation A0 was ~ 27 dB. However, the experimental value of A0 was about ~ 23 dB. The reasons for this discrepancy will be discussed elsewhere.

The cross-talk performance of the single switch depends on the input light polarization as well as on the state of LC pixel. Therefore there are totally four possible states of single binary switch as shown in the Figure. 4.

From the Fig. 4 it is clear that the highest cross-talk is in case of horizontal input polarization and unswitched pixel (Fig. 4d).

4 Cross-talk of 4 x 4 Matrix Switch

The important feature of the proposed architecture is that all input channels come to the same quadrant of the switch corresponding to the Output O0, therefore the crosstalk will not depend on input channel index (Ix), but on the final (output) destination.
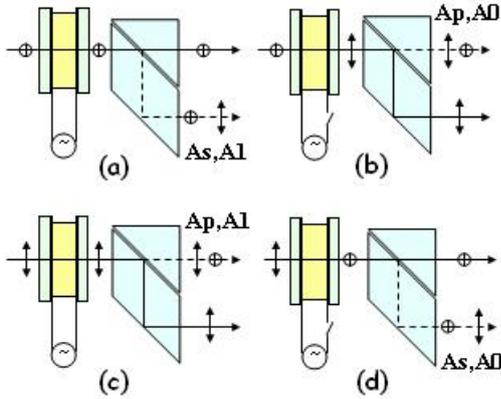

Figure 4 Four different cross-talk sources in binary optical switch.

Let consider that all the input channels are addressed to the outputs of the same index, e.g. *I0* to *O0*, *I1* to *O1*, etc…, as shown in the Fig. 5. The main routs are shown by solid lines, while the parasitic (attenuated) beams are dashed.

Let's introduce an attenuation parameter array A(m,n) for the light intensity (attenuation) in the output *On* which come from any input channel addressed to the output *Om*. These intensities and corresponding indices *m,n* are shown in the Fig.3a. According such indexation the diagonal elements of array A(m,n), m=n correspond to the addressed beams and indicate an insertion loss, while non-diagonal elements of array A(m,n), m≠n correspond to the parasitic beams and are related to the cross-talk.

First, let's find parasitic beams destinations from any input channel (e.g. *I0*) addressed to output *O0*. (Fig. 3a, left-bottom corner).

The main beam of input channel *I0* at 1st stage (see Fig. 5) passes straightforward through the LBS and produces parasitic (shifted) beam which consists of two components (see Fig. 4a): vertically polarized As(v) and horizontally polarized A1(h).

Figure 4 Propagations of the main and parasitic beams in the 4 x 4 switch

They will be rotated by second SLM's pixel on 90° and addressed to two outputs O1 and O3 correspondingly, i.e.
$$A(0,1) = As(h), A(0,3) = A1(v)$$
The main beam polarization will be rotated by second SLM's pixel at 2nd stage, then will pass straightforward through the LBS and produce parasitic (shifted) beam which consists of two components (see Fig. 3d): vertically polarized A0(v) and horizontally polarized As(h). Both of them will be addressed to the output *O2*, i.e.
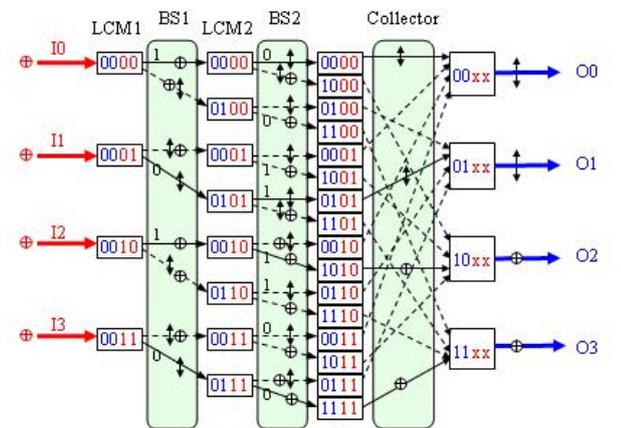$$A(0,2) = A0(v) \& As(h)$$
Finally the parasitic light intensities from any input channel addressed to the O0 - A(0,x) are:

A(0,1) = As(h), A(0,3) = A1(v) and A(0,2) = A0(v) & As(h)

Similarly, the parasitic lights from any input channel addressed to the O1 - A(1,x) are:

A(1,0) = Ap(h), A(1,2) = A0(v), A(1,3) = A1(v) & As(h)

Similarly, A(2,x) and A(3,x) are:

A(2,1) = A1(h), A(2,3) = As(v) and A(2,0) = A0(v) & Ap(h)

A(3,0) = A0(h), A(3,2) = Ap(v) and A(3,1) = Ap(v) & A0(h)

Now we can find the cross-talk in *i-th* Output, *A(i)* by collecting together the terms A(m,n) with *n = i* or A(x,i).

The Cross-talk in Output *O0, A(0)* consists of three components:

A(1,0) = Ap(h) & A(2,0) = A0(v) & Ap(h) & A(3,0) = A0(h), or simply 2 Ap(h), A0(h) and A0(v)

Cross-talk in Output *O1*:
$$As(h) \& A1(h) \& Ap(v) \& A0(h)$$
Cross-talk in Output *O2*:
$$2 A0(v) \& As(h) \& Ap(v)$$
Cross-talk in Output *O3*:
$$2 A1(v) \& As(h) \& As(v)$$

An approximate values of simulated cross-talk are shown in the Table I.

Output channel	Cross-talk	
	Sources	Value (dB)
O0	~ 2 A0	~ 20
O1	~As & A0	~18
O2	~ As & 2A0	~17
O3	~ 2As	16

Table I Values of simulated cross-talk from the derived formula.

The experimental cross-talk can be found by measuring all 16 components of output intensities array A(m.n). These measurements are summarized in the Table II.

m \ n		0	1	2	3
	A(m,n)	A (x, 0)	A (x, 1)	A (x, 2)	A (x, 3)
0	A (0, x)	1.23	21.08	18.02	23.04
1	A (1, x)	33.36	1.93	26.83	20.63
2	A (2, x)	23.74	23.18	1.39	20.10
3	A (3, x)	27.34	22.72	31.36	1.69

Table II Measured value of Attenuation (dB) arising from parasitic beam propagation.

Finally using the values of A(m,n) components wecan define the cross-talk in the output channels

Output channel	Cross-talk, dB
O0	21.83
O1	17.44
O2	17.29
O3	16.29

Table III Cross-Talk of all the output channels arising from parasitic beams.

5 The Cross-talk Cleaning

An important feature of this switching architecture is that the main beams in outputs O0,O1 are horizontally polarized. Therefore by placing horizontal polarizer after the second SLM the cross-talks A(0),A(1) will be reduced to: A(0)=2 Ap(h) & A0(h) and A(1)= As(h) & A1(h) & A0(h).

Similarly, the main beams in outputs O2,O3 are vertically polarized, therefore by placing vertical polarizer the cross-talks A(2), A(3) will be reduced to:

$$A(2) = 2 \ A0(v) \ \& \ Ap(v)$$

and

$$A(3) = 2 \ A1(v) \ \& \ As(v)$$

Output channel	Cross-talk, dB
O0	22.37
O1	17.90
O2	21.58
O3	18.57

Table IV Simulated values of cross-talk after cleaning.

m \ n		0	1	2	3
	A(m,n)	A (x, 0)	A (x, 1)	A (x, 2)	A (x, 3)
0	A (0, x)	2.88	22.51	22.36	20.28
1	A (1, x)	26.37	3.11	26.91	26.67
2	A (2, x)	26.52	21.82	3.51	21.03
3	A (3, x)	27.07	23.29	27.43	2.81

Table V Attenuation after introduction of a polarizer.

Output channel	Cross-talk, dB
O0	21.85
O1	17.71
O2	20.14
O3	17.10

Table VI Cross-Talk of all the output channels after introducing the polarizer.

The further simplification can be made noticing that the attenuations A1 and Ap are much higher than A0 and As, therefore they can be ignored, i.e.

A(0) = A0(h), A(1) = As(h) & A0(h), A(2) = 2 A0(v),

and

$$A(3) = As(v)$$

The further improvement of the cross-talk can achieved by placing another SLM and polarizer before the output collectors. The pixels of the final SLM rotate (if necessary) the polarizations of the main and parasitic beams, i.e. the parasitic beams will be attenuated once more by final polarizer.

In this case the worst cross-talk is about -(As+A0), or –(19 dB +22 dB) = -41 dB.

Therefore the overall crosstalk will be as good as (or even better) than for individual optical switch and satisfy the requirements for fibre-optic communication networks.

6 Insertion Loss

The insertion loss of the switch depends mostly on the number of glass-air surfaces, the use of antireflection coatings and/or immersion oil. For worst case the loss due to reflection on glass-air border is ~0.18 dB. Our prototype consists of 8 glass-air surfaces with total loss of ~1.42 dB. The experimental value of insertion loss was found as ~ 0.95 dB, which is close to the expected value.

7 Conclusion

In present article we described only the principles of new approach for LC based matrix optical switch, which shows several advantages over the conventional cross-point architecture such as: cost, complexity, size, adjustment, and optical performance.

The simulations of the cross-talk and experimental values were measured on 4 x 4 channel prototype, but will the same for lager switches.

The insertion loss for larger switches will be higher that for 4 x 4 switch due to the higher number of switching stages, i.e. twice higher for 16 x 16 switch and three time higher for 64 x 64 switch.

The practical design/application of this scheme requires further research and development of other important aspects/ components, which were not considered in present paper, such as collector lenses, fiber coupling, polarizers, SLMs, etc.

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