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Pure Non-Blocking LC Based Matrix Optical Switch for All-Optical Fibre Networks

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New pure non-blocking matrix optical switch scheme for fiber networks is presented. The optical switch is based on conventional LCD technology, where the each pixel controls the polarization state of the light beam. The suggested switch offers several advantages over the conventional cross-point architecture such as: cost; complexity; size; adjustment; and optical performance

INTRODUCTION

Explosive growth in data communications is changing the requirements for the networks, demanding for wider and wider bandwidth. At present, more and more communication transmission infrastructures are based on optical fibre links with practically unlimited bandwidth. The core part of any optical fibre network is an optical switch that allows to route signals between different terminals. This demand is encouraging a new generation of technologies designed to make networks faster, more reliable and more scalable.

The optical switches can be classified into two categories. The first category changes the optical signal into electrical and performs switching function before changing it back to optical. Such an optical-electrical-optical (OEO) switch, or opaque switch, provides a very high degree of flexibility. On the other hand, the opaque switches,

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have an increasing cost per port as bandwidth increases and could become high cost centers in the future network.

The second category is a pure optical (or Photonic) switch where optical-electrical-optical conversion is not necessary. 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 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. There are a number of photonic switching technologies, including: Micro-Electro-Mechanical Systems (MEMS), Thermo-optics (e.g., bubble) technology, Liquid Crystal switching, etc... Currently the optical switching is performed by Micro Electro–Mechanical Switches (MEMS), which are based on mechanical movements of the mirrors. This limits the switching speed and lifetime of such optical switches.

On the other hand, the optical switching can be easily achieved with help of Liquid Crystals, utilizing a number of different electro-optic effects such as: TN; total reflection [1]; FLC [2]; holographic; cholesteric mirrors [3]; etc... Although binary (1-to-2 or 2-to-2) LC based optical switches are well known, the larger (matrix) optical switches are not yet commercialised. The main reason is follows. In conventional matrix approach to perform non-blocking N to N switching it is necessary to use a matrix with $N \times N$ single Switching Elements (SE), each placed on the cross-point of input and output channels. This 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. Nevertheless this approach has also several key drawbacks:

- Large number of single switches $S = N^2$. This dramatically increases the total cost of the matrix and complicates its adjustment and reliability.
- The light beam is travelling through N switches accumulating extra insertion loss and cross-talk. In other words, even if the single switch's performance is rather fascinating – the total matrix switch performance will be unacceptable.

The last statement can be illustrated by the following example. Let us consider cross-point $N \times N$ ports optical switch and the contrast ratio of the single switch $K = 1000$, which corresponds to cross-talk $CT_1 = 10 \log(1/K) = -30 \, \text{dB}$. This means that about 0.1% of the input power flows in the wrong direction. Although such a small amount

residual (strain) light does not affect much the power in the output channel (or insertion losses) but it significantly worsens the overall cross-talk ratio of the proposed matrix switch.

The overall crosstalk $N \times N$ ports matrix switch is

$$CT_N = 10 \cdot \log(N - 1) + CT_1 \qquad (1)$$

Therefore for practical 16- and 64-ports switches the final crosstalk will be $CT_{16} = -18.24 \, \text{dB}$ and $CT_{64} = -12 \, \text{dB}$ correspondingly.

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.

BASIC SWITCH DESCRIPTION

Binary Switching Element

The core element of the proposed scheme is TN LC cell in conjunction with lateral displacement beamsplitter (LBS) as shown in the Figure 1.
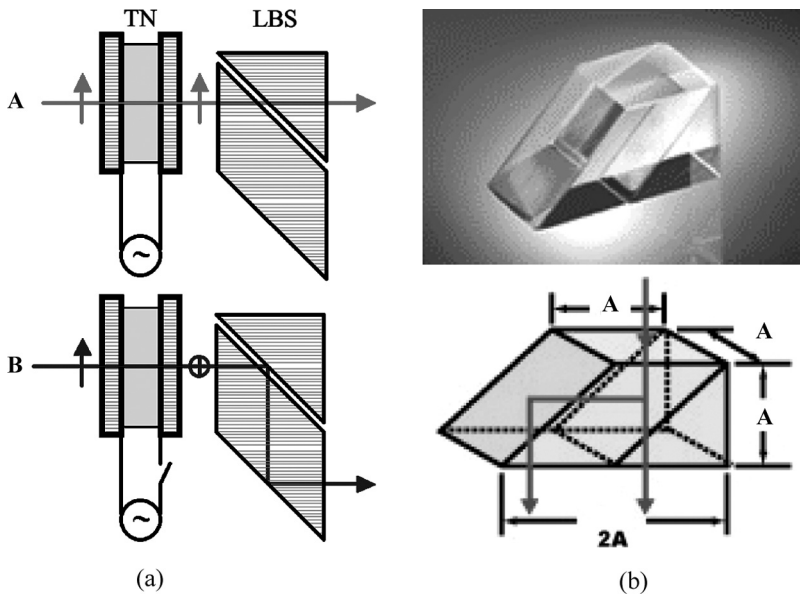

FIGURE 1 (a) Schematic diagram of bypass/shift optical switch based on TN cell and (b) TECH SPEC$^{\text{TM}}$ Lateral Displacement Beamsplitters (http://www.edmundoptics.com/WE/).

When the voltage is applied to LC pixel (A case) the 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 (B case), 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.

In matrix optical switch we suggested to use a simple and inexpensive LC matrix (LCM) in conjunction with lateral displacement beamsplitter (LBS) as a core part of Switching Array (SA). Such LCM, performs parallel and independent switching of all input optical channels (N-to-2N), where one pixel of the matrix performs 1-to-2 binary switching.
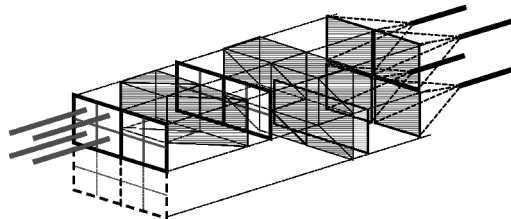
Basic Matrix Switch

The architecture and performance of proposed switch in simplest (basic) 4×4 port matrix switch is shown in the Figure 2. The matrix optical switch can be assembled by simple stacking two SAs the first of them performs horizontal (right) shift on 2-pixel distance and the second one – vertical (down) shift; the birefringent film; four square-shaped collector lenses and four output fibres.

LCM consists of 16 (4×4) pixels which are arranged in square fashion in four 4-pixels groups (Fig. 2a). Each pixel has 4-digit code (index): $klmn$ where kl defines the index of the group and mn defines the index within each group. 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., $2k + l$).

0000	0001	0100	0101
0010	0011	0110	0111
1000	1001	1100	1101
1010	1011	1110	1111

(a)   (b)

FIGURE 2 (a) Spatial distribution of input optical routs and (b) total construction of 4×4 matrix switch.
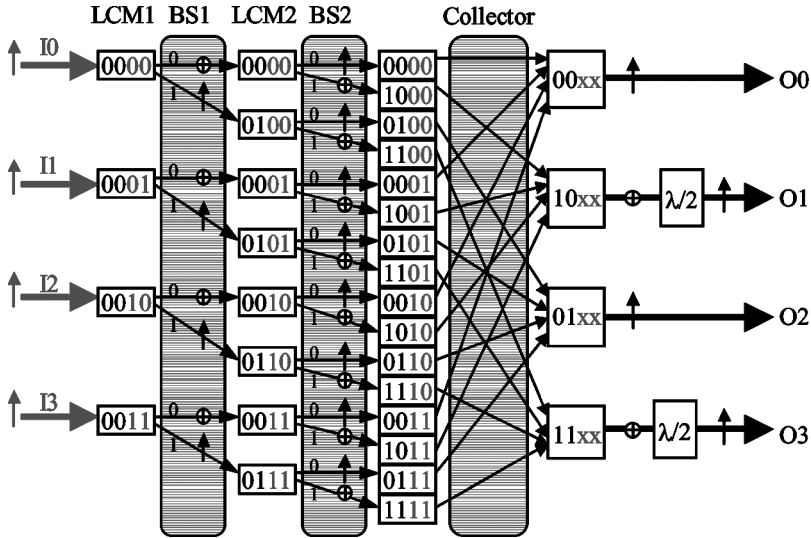
LCM1 BS1 LCM2 BS2 Collector

FIGURE 3 Switching network for non-blocking 4×4 channels optical switch.

Such indexing provides simple routing algorithm e.g. $k \neq m$ is a condition for horizontal switching and $l \neq m$ – for vertical switching. Horizontal switching (shift) occurs when the light polarisation is vertical ($\uparrow$) and vertical switching – for horizontal polarization ($+$). The TN LC pixel rotates polarisation if there is no voltage on it (0) and leaves polarization without change if voltage is applied (1). The complete switching network is shown in the Figure 3.

The final polarization of the output channels is vertical if k = 0 and horizontal if k = 1. If necessary the output polarisation of the k = 1 channels can be easily corrected (i.e., changed to the vertical) by introduction the half-wave ($\lambda/2$) birefringent plate (film) or extra TN LCM. The actual position of this film is on the rear side, bottom half of the second (last) beamsplitters (Fig. 2b).

LARGER OPTICAL SWITCHES

The architecture of larger optical switches is similar to the described 4×4 switch (N = 4, n = 2) with only one important difference – it needs extra pair of beamsplitters with different (double) lateral displacement. Lets consider larger 16×16 optical switch (N = 16, n = 4 and $N = n^2$). In this case the LCM consists of 256 (16×16) pixels as shown in the Figure 4.

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0000	0001	0002	0003	0100	0101	0102	0103	0200	0201	0202	0203	0300	0301	0302	0303
0010	0011	0012	0013	0110	0111	0112	0113	0210	0211	0212	0213	0310	0311	0312	0313
0020	0021	0022	0023	0120	0121	0122	0123	0220	0221	0222	0223	0320	0321	0322	0323
0030	0031	0032	0033	0130	0131	0132	0133	0230	0231	0232	0233	0330	0331	0332	0333
1000	1001	1002	1003	1100	1101	1102	1103	1200	1201	1202	1203	1300	1301	1302	1303
1010	1011	1012	1013	1110	1111	1112	1113	1210	1211	1212	1213	1310	1311	1312	1313
1020	1021	1022	1023	1120	1121	1122	1123	1220	1221	1222	1223	1320	1321	1322	1323
1030	1031	1032	1033	1130	1131	1132	1133	1230	1231	1232	1233	1330	1331	1332	1333
2000	2001	2002	2003	2100	2101	2102	2103	2200	2201	2202	2203	2300	2301	2302	2303
2010	2011	2012	2013	2110	2111	2112	2113	2210	2211	2212	2213	2310	2311	2312	2313
2020	2021	2022	2023	2120	2121	2122	2123	2220	2221	2222	2223	2320	2321	2322	2323
2030	2031	2032	2033	2130	2131	2132	2133	2230	2231	2232	2233	2330	2331	2332	2333
3000	3001	3002	3003	3100	3101	3102	3103	3200	3201	3202	3203	3300	3301	3302	3303
3010	3011	3012	3013	3110	3111	3112	3113	3210	3211	3212	3213	3310	3311	3312	3313
3020	3021	3022	3023	3120	3121	3122	3123	3220	3221	3222	3223	3320	3321	3322	3323
3030	3031	3032	3033	3130	3131	3132	3133	3230	3231	3232	3233	3330	3331	3332	3333

FIGURE 4 16×16-pixel LC matrix. Pixel Index: *klmn*. Input Channels: *I0 − I15* ($I = 4m + n$). Output Channels: *O0 − O15* ($O = 4k + l$).

The pixels are again arranged in square fashion in sixteen 16-pixels (4×4) groups. The pixels indices are the same as for the described switch. The basic beamsplitter shifts a beam on 4 pixels (i.e., one group) down/right. To address the first input channel *I0* to the output *O15* it is necessary to use 6 such beamsplitters: three for horizontal shift and other three – for vertical. In general, number of LCMs (M) $M = 2·(n − 1)$. Nevertheless, there is a way to decrease the total number of LCMs and beamsplitters. This can be done by two different pairs of beamsplitters: first (basic) pair (BSH1 and BSV1) shifts on 4 pixels (i.e., one group) and the second is pair of "double strength" BS (BSH2 and BSV2) which shifts on 8 pixels (i.e., two groups). The construction of 16×16 optical switch is shown in the Figure 5.

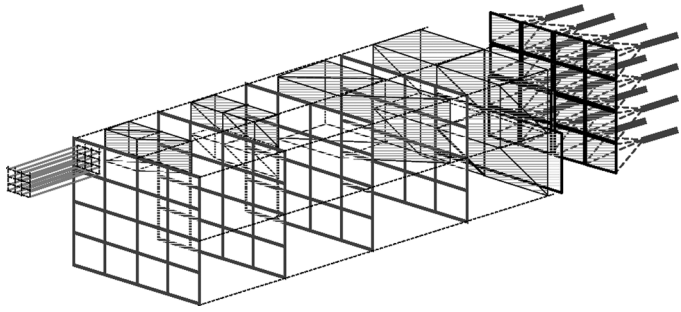The switching network for non-blocking 16×16 channels optical switch is shown in the Figure 6. Similar to 4×4 switch, the final

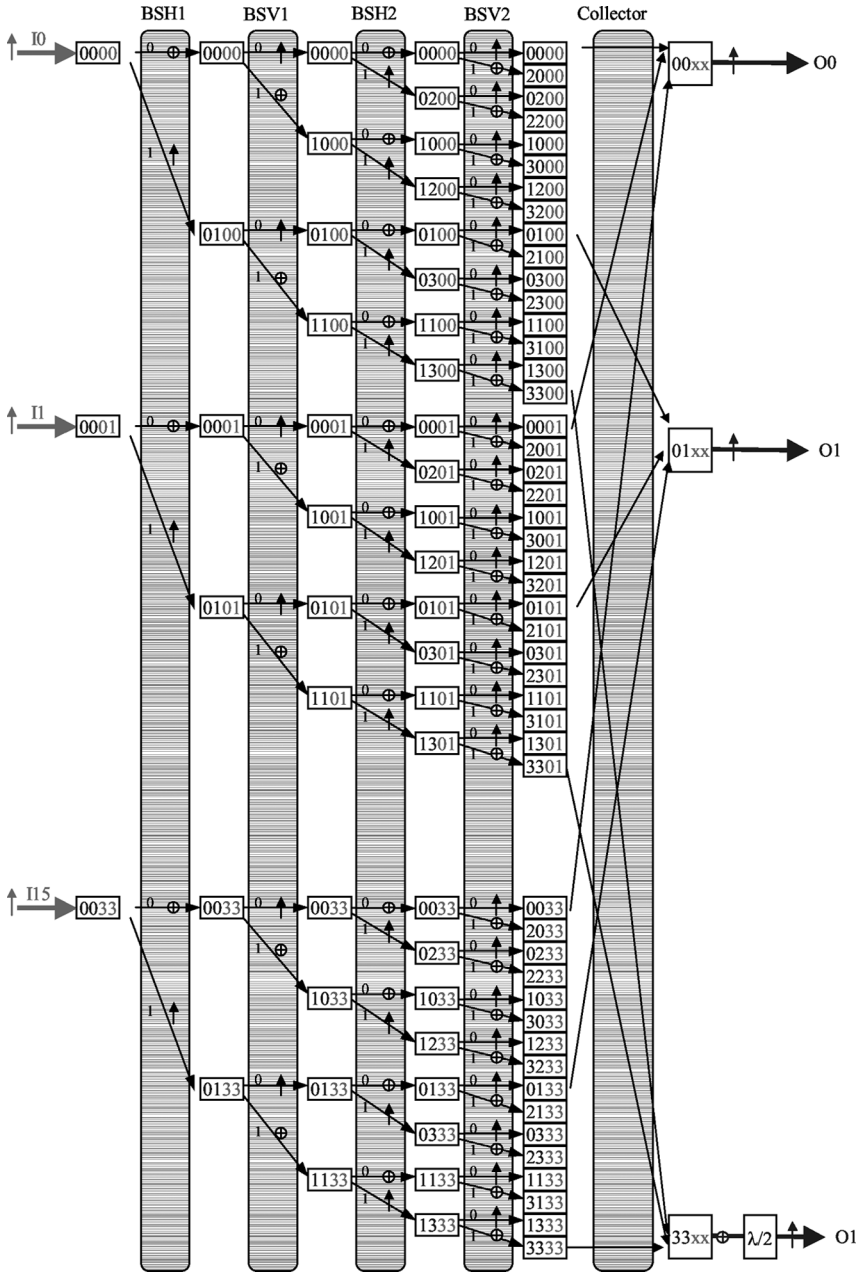**FIGURE 5** The construction of 16×16-ports LC matrix switch.

FIGURE 6 Switching network for non-blocking 16×16 channels optical switch.

polarization of the output channels with k = 0 or 1 is vertical and k = 2,3 is horizontal. The output polarisation of the k = 2,3 channels can be easily corrected by placing the half-wave ($\lambda/2$) birefringent plate (film) on the rear side, bottom half of the forth (last) beamsplitter.

Similarly larger 64×64 optical switch (N = 64, n = 8) consists of 3 different pairs of beamsplitters: first (basic) pair (BSH1 and BSV1) shifts on 8 pixels (i.e., one group), the second is pair of "double strength" BS (BSH2 and BSV2) which shifts on 16 pixels (i.e., two groups) and the third is a pair of "quarto-strength" BS (BSH4 and BSV4) which shifts on 32 pixels (i.e., four groups). In this scheme n (n = 2, 4, 8, . . .) is a power of 2^q (q = 1, 2, 3) and the total number of SAs is

$$M = 2 \cdot \log_2(\sqrt{N}) = 2 \cdot \log_2(n) = 2 \cdot q. \tag{2}$$

FURTHER IMPROVEMENTS

The proposed switching scheme possesses some features and peculiarities enabling further useful modifications.

LCM reduction. In matrix switch the "active" or switching area of LCM depends on the switching stage, i.e., for the first stage it is N (n × n)–pixels group of whole N × N–pixels matrix with index 00xx (see Fig. 2). The active area of the second stage consists of two groups with the indices 00xx and 01xx. In general, in N × N ports matrix switch the active area of the last stage is just upper half of N × N pixels LCM. Therefore N × N ports matrix switch needs N-columns by N/2-rows LCMs.

Mosaic addressing. In general, N × N ports matrix switch consists of 2q N × N/2-pixels (or $N^2/2$) LCMs. Therefore for practical matrix switches (16 or 64-ports) the total number of pixels becomes rather large and LCM needs matrix addressing rather than simplest mosaic addressing. The passive-matrix addressing reduces the quality (i.e., cross-talk) of the optical switching, while active-matrix addressing increases the cost of LCM. This drawback can be cured by driving the pixels with indices *xxmn* (e.g., 0000, 0100, 1000 and 1100, see Fig. 2a) by the same control line, i.e., connecting these pixels to the same control line. In this case the number of independent control lines reduces form $N^2/2$ to just N enabling simple and inexpensive mosaic addressing.

If necessary the simplest TN LCMs can be replaced by much faster FLC matrices or higher quality vertical aligned (VA) LCMs or other LC based switches.

THE CROSS-TALK CLEANING

It was mentioned that the overall matrix switch crosstalk is worse than the crosstalk of the single switch and depends on the number of stages that the beams pass through (Eq. (1)) and becomes unacceptably low in cross-point matrix switch. The suggested matrix switch offers much better overall crosstalk, due to lower number of switching stages (compare M and N, Eq. (2))

In general, assuming that CT_1 is a cross-talk of the single switch (stage), the overall crosstalk of the N-channels optical switch (CT_N) is:

$$CT_N = 10 \cdot \log(\sqrt{N-1}) + CT_1 \approx 10 \cdot \log(n)$$
$$+ CT_1 = 10 \cdot \log_2(n)/3.32 + CT_1 \approx 3q - CT_1 \qquad (3)$$

Thus the overall crosstalk of 64-channels switch (N = 64, n = 8, q = 3) will be about $-21\,\text{dB}$, which is rather low for practical application.

It is possible to eliminate the parasitic effect of all the residual light beams by introducing the cross-talk removal polarizer between the final (last) SA and collectors as shown in the Figure 7. Let us consider
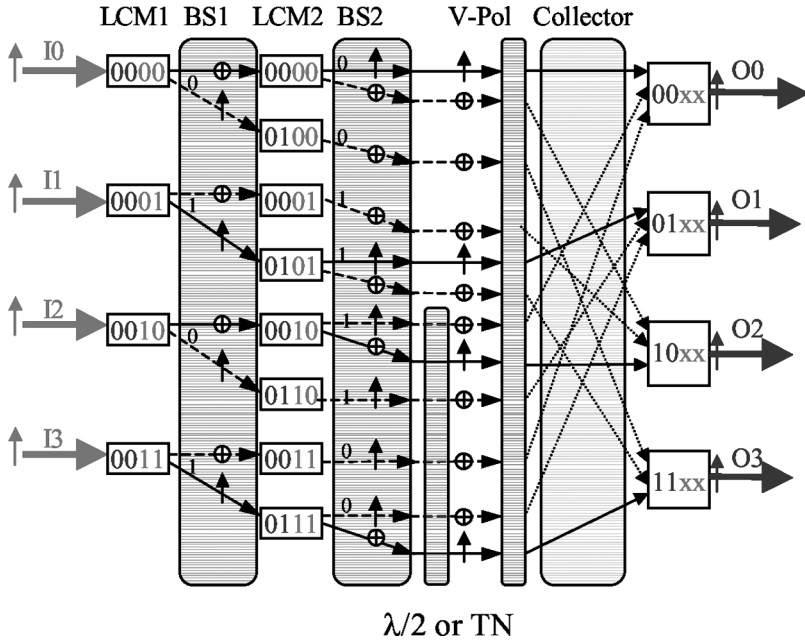

FIGURE 7 Polarization states and crosstalk cleaning in blocking 4×4 channels optical switch.

that 4-ports switch is configured to connect the input ports to the output ports with the same number, i.e. I0 to O0, I1 to O1, etc. The main beam traces are drawn as solid lines (arrows), while the residuals beams as dashed lines. It is interesting to find (see Fig. 7) that all the main beams in upper half of the switch are vertically polarised, while all the residual beams are horizontally polarised. The opposite is valid for the bottom half of the switch. After passing through the $\lambda/2$ (or TN) layer the polarisations of all main beams will change to the vertical and all residual beams to horizontal. If the axis of this polarizer is vertical, all the residual channels will not pass through it to the collectors. Therefore the overall crosstalk will be as good as (or even better) than for individual optical switch.

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

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