# Double-layer networks with holographic optical switches

Jiun-Shiou Deng, Ming-Feng Lu, and Yang-Tung Huang

The double-layer networks have the advantages of being strictly nonblocking and having a simpler routing algorithm, the lowest system insertion loss, a zero differential loss, fewer drivers, fewer interconnection lines, fewer crossovers, and the best signal-to-noise-ratio characteristic compared with any nondilated network. Using holographic optical switches to construct these networks not only eliminates all interconnection lines and crossovers but also reduces the number of drivers. © 2004 Optical Society of America

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## 1. Introduction

Compared with electronic switching systems, photonic switching systems have large bandwidths. Hence they are suitable for communications and computing systems. Several networks have been proposed for optical space switching. The crossbar network[1,2] uses the simplest routing algorithm, but its differential loss is not zero. Furthermore its signal-to-noise ratio (SNR) not only decreases because of the increase in the network dimension but also decreases quickly because of the insertion loss of switches. Although the Benes network[3] is characterized by the lowest system insertion loss and the fewest required switches and drivers, it is a rearrangeable nonblocking network that needs a more complex routing algorithm. The double-layer network (DLN) has some advantages, such as being strictly nonblocking and having a simpler routing algorithm, the lowest system insertion loss, a zero differential loss, fewer drivers, fewer crossovers, and the best SNR compared with any nondilated network.[4,5] A DLN is a recursive structure network as shown in Fig. 1.[4] Figure 2 shows a 4 × 4 double-layer network with an ordered channel and switch numbers in which the $(N/2) \times (N/2)$ subnetwork is a $2 \times 2$ switch.

The holographic optical switches[6–13] (HOSs) are three-dimensional devices. The compactness and flexibility of the HOSs are also important characteristics. In this paper we introduce a new approach to the DLN, which is constructed by these HOSs. This approach not only reduces the number of drivers and eliminates all interconnection lines between stages but also maintains the original advantages.

## 2. Holographic Optical Switches

A HOS consists of two electro-optic halfwave plates (EOHWPs), such as flow line concentrators[14–16] and one holographic polarization beam splitter (PBS) in which two symmetric polarization-selective grating pairs are formed on a dielectric substrate. The holographic PBS was sandwiched between two EOHWPs as shown in Fig. 3. In a holographic PBS the diffraction angle in the film medium is $\theta_D$ and the Bragg reconstruction input angle is 0°, i.e., the input beam is normally incident on the device. On the other hand, in the input coupling the reconstruction angle is $\theta_D$ and the output diffraction beam is also normal to the device as shown in Fig. 3.

A high polarization-selective property (0% and 100% diffraction for $s$ and $p$ fields, respectively, or 100% and 0% diffraction for $s$ and $p$ fields, respectively) can be designed and has been fabricated,[6–14] and we use the former devices with $s$ transition and $p$ diffraction in our system's design examples. In this holographic PBS the distance between two channels is $d$ and the corresponding thickness of the dielectric substrate is $t$. The relationship between these two parameters is

$$t = d \times \cot \theta_D, \tag{1}$$

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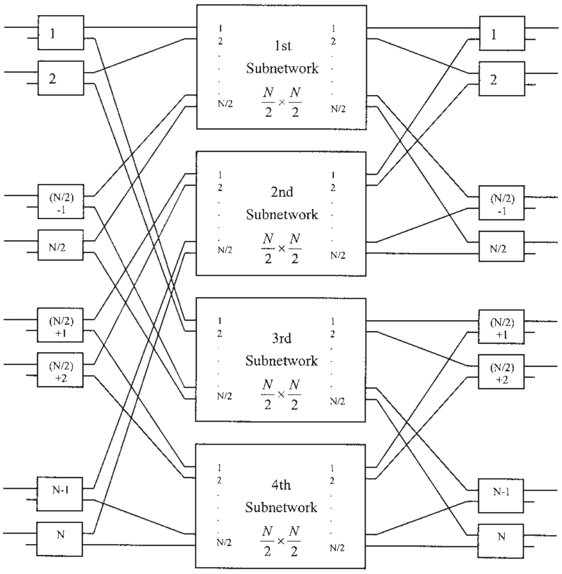

Fig. 1. $N \times N$ double-layer network.

where $\theta_D$ is 41.4° in this structure. In other words, when the distance between these two channels in a switch is changed to $2d$, the thickness of the dielectric substrate becomes $2t$.

For the remaining same polarization state at input and output, this switch needs two EOHWPs, and these two EOHWPs are controlled by the same driver. Figures 3(a) and 3(b) show two states of a basic HOS. In this example, the initial input and final output beams remain $s$ polarized. When EOHWPs are inactive the beam polarizations are not changed. The beam polarizations will not be changed by the holographic gratings. In this case the switch provides straight connections as in Fig. 3(a). When EOHWPs are active the beam polarization orientations are rotated by 90° and the polarizations of this beam are $p$ polarized. This beam is diffracted by the input grating and normally coupled out with a conjugate diffraction by the output grating. In this case the switch provides swap connections as in Fig. 3(b). Obviously this HOS provides a switching function for bidirectional connections. To use these HOSs to design an interconnection network, we used the simplified symbol of this switch shown in Fig. 3(c).

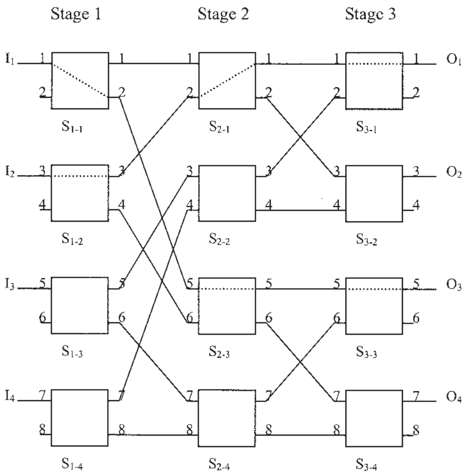

Fig. 2. A 4 × 4 double-layer network with ordered channel and switch numbers. In this example, channels $I_1$ and $I_2$ are connected to channels $O_3$ and $O_1$, respectively.

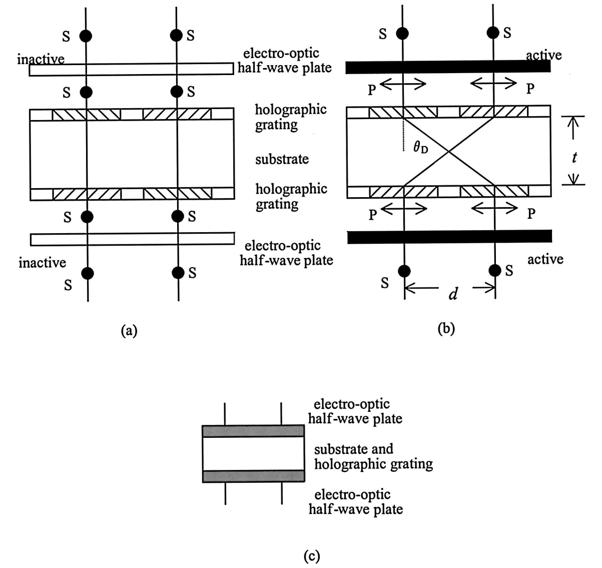

Fig. 3. Holographic optical switch with two electro-optic halfwave plates to maintain optical beam polarization: (a) straight state, (b) swap state, (c) simplified symbol.

## 3. Double-Layer Network with Holographic Optical Switches

A 4 × 4 DLN with ordered channels and switch numbers is shown in Fig. 2 in which $S_{i-j}$ represents the $j$th switch in stage $i$, $I_m$ represents input channel $m$, and $O_n$ represents output channel $n$. Its channel connection table and transformation table are shown in Table 1 and Fig. 4, respectively. The connection table describes the connection configuration between

**Table 1. Channel Connection Table between Stages for a 4 × 4 Double-Layer Network**

| Output Channel of First Stage to Input Channel of Second Stage | | Output Channel of Second Stage to Input Channel of Third Stage | |
|---|---|---|---|
| Output Channel of First Stage | Input Channel of Second Stage | Output Channel of Second Stage | Input Channel of Third Stage |
| 1 | $1 + 4 \times 0 = 1$ | 1 | $1 + 2 \times 0 = 1$ |
| 2 | $1 + 4 \times 1 = 5$ | 2 | $1 + 2 \times 1 = 3$ |
| 3 | $2 + 4 \times 0 = 2$ | 3 | $2 + 2 \times 0 = 2$ |
| 4 | $2 + 4 \times 1 = 6$ | 4 | $2 + 2 \times 1 = 4$ |
| 5 | $3 + 4 \times 0 = 3$ | 5 | $5 + 2 \times 0 = 5$ |
| 6 | $3 + 4 \times 1 = 7$ | 6 | $5 + 2 \times 1 = 7$ |
| 7 | $4 + 4 \times 0 = 4$ | 7 | $6 + 2 \times 0 = 6$ |
| 8 | $4 + 4 \times 1 = 8$ | 8 | $6 + 2 \times 1 = 8$ |

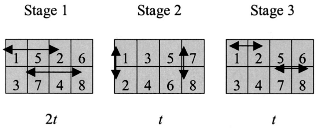

Fig. 4. Transformation table of a 4 × 4 double-layer network.

two adjacent stages, and the transformation table shows the channels' allocation in each stage. The transformation table is derived from the connection configuration between stages. As shown in Fig. 2 output channel 1 at stage 1 is connected to the input of channel 1 at stage 2, and the output of channel 2 at stage 1 is connected to the input of channel 5 at stage 2. Moreover output channels 3, 4, 5, 6, 7, and 8 at stage 1 are connected to input channels 2, 6, 3, 7, 4, and 8 at stage 2, respectively. Output channels 1, 2, 3, 4, 5, 6, 7, and 8 at stage 2 are connected to input channels 1, 3, 2, 4, 5, 7, 6, and 8 at stage 3, respectively. The connection table shows the same connection states with Fig. 2. Note that the two channels labeled 1 and 2 represent two different channels in a specific 2 × 2 switching unit, while channels 3 and 4 do the other. This relationship is designated by arrows.

After the connection table shown in Table 1 is obtained, the transformation table presenting the relative position of the channels in each stage can be derived. Because all channels 1's in stages 1, 2, and 3 are connected, they have been allocated at the same position. Since output channel 3 at stage 1 is connected to input channel 2 at stage 2, the position of channel 2 at stage 2 has been placed at the same position as channel 3 at stage 1. For the same reason, channel 3 at stage 3 has been allocated at the same position as channel 2 at stage 2. After completing all channel allocations, the transformation table of a 4 × 4 DLN can be accomplished as shown in Fig. 4. In Fig. 4 $t$ represents the thickness of the dielectric substrate described in Section 2.

When HOSs are used to build a DLN, the fixed interconnection lines between stages must be considered. Instead of using additional elements to change the propagation directions of light beams after each stage for these fixed interconnections, we employ two-dimensional input channel layouts and implement the connections between stages by an appropriate grating-orientation arrangement of each switching unit at each stage. Then the network can be constructed by piling up those elements. A three-dimensional structure with HOSs is shown in Fig. 5. As shown in Fig. 5, there is no interconnection line in this compact structure. Hence there is no crossover in this structure too.

The thickness $t$ of the dielectric substrate is determined based on the distance between two channels in a HOS. When two channels in a switch are adjacent, such as stages 2 and 3, the distance between these two channels is $d$, and the corresponding thickness of the dielectric substrate of both stages 2 and 3 are $t$, which can be obtained from Eq. (1). However, channels 1 and 2 in stage 1 are not adjacent. The distance between these two channels is $2d$, and the corresponding thickness of the dielectric substrate of stage 1 is $2t$. The thickness of the dielectric substrate for each stage is also shown in Figs. 4 and 5.

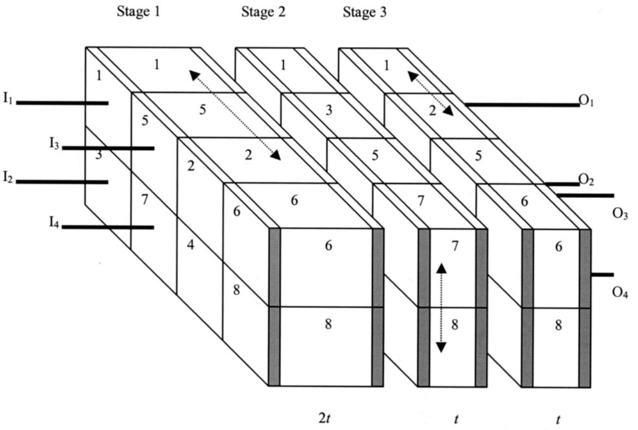

Fig. 5. Three-dimensional compact configuration for a 4 × 4 double-layer network.

An 8 × 8 DLN with ordered channel numbers is shown in Fig. 6. Its channel connection table and transformation table are shown in Table 2 and Fig. 7, respectively. As in Table 1, in Table 2 we describe the connection states in Fig. 6. The transformation

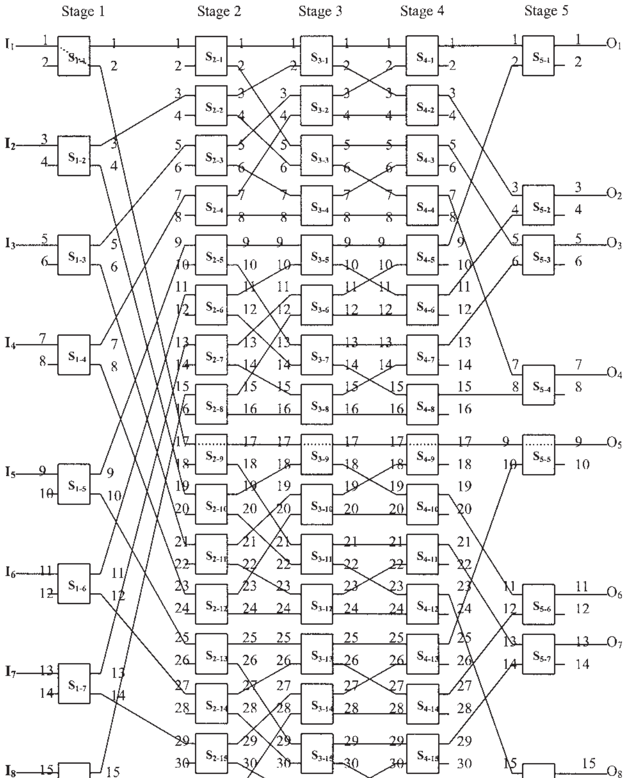

Fig. 6. An 8 × 8 double-layer network with ordered channel numbers.

Table 2. Channel Connection Table between Stages for an 8 × 8 Double-Layer Network

| Output Channel of First Stage to Input Channel of Second Stage | | Output Channel of Second Stage to Input Channel of Third Stage | | Output Channel of Third Stage to Input Channel of Fourth Stage | | Output Channel of Fourth Stage to Input Channel of Fifth Stage | |
|---|---|---|---|---|---|---|---|
| Output Channel of First Stage | Input Channel of Second Stage | Output Channel of Second Stage | Input Channel of Third Stage | Output Channel of Third Stage | Input Channel of Fourth Stage | Output Channel of Fourth Stage | Input Channel of Fifth Stage |
| 1 | $1 + 15 \times 0 = 1$ | 1 | $1 + 4 \times 0 = 1$ | 1 | $1 + 2 \times 0 = 1$ | 1 | $1 - 0 \times 0 = 1$ |
| 2 | $2 + 15 \times 1 = 17$ | 2 | $1 + 4 \times 1 = 5$ | 2 | $1 + 2 \times 1 = 3$ | 2 | $3 - 0 \times 0 = 3$ |
| 3 | $3 + 15 \times 0 = 3$ | 3 | $2 + 4 \times 0 = 2$ | 3 | $2 + 2 \times 0 = 2$ | 3 | $5 - 0 \times 0 = 5$ |
| 4 | $4 + 15 \times 1 = 19$ | 4 | $2 + 4 \times 1 = 6$ | 4 | $2 + 2 \times 1 = 4$ | 4 | $7 - 0 \times 0 = 7$ |
| 5 | $5 + 15 \times 0 = 5$ | 5 | $3 + 4 \times 0 = 3$ | 5 | $5 + 2 \times 0 = 5$ | 5 | $9 - 7 \times 1 = 2$ |
| 6 | $6 + 15 \times 1 = 21$ | 6 | $3 + 4 \times 1 = 7$ | 6 | $5 + 2 \times 1 = 7$ | 6 | $11 - 7 \times 1 = 4$ |
| 7 | $7 + 15 \times 0 = 7$ | 7 | $4 + 4 \times 0 = 4$ | 7 | $6 + 2 \times 0 = 6$ | 7 | $13 - 7 \times 1 = 6$ |
| 8 | $8 + 15 \times 1 = 23$ | 8 | $4 + 4 \times 1 = 8$ | 8 | $6 + 2 \times 1 = 8$ | 8 | $15 - 7 \times 1 = 8$ |
| 9 | $9 + 15 \times 0 = 9$ | 9 | $9 + 4 \times 0 = 9$ | 9 | $9 + 2 \times 0 = 9$ | 9 | $17 - 8 \times 0 = 9$ |
| 10 | $10 + 15 \times 1 = 25$ | 10 | $9 + 4 \times 1 = 13$ | 10 | $9 + 2 \times 1 = 11$ | 10 | $19 - 8 \times 0 = 11$ |
| 11 | $11 + 15 \times 0 = 11$ | 11 | $10 + 4 \times 0 = 10$ | 11 | $10 + 2 \times 0 = 10$ | 11 | $21 - 8 \times 0 = 13$ |
| 12 | $12 + 15 \times 1 = 27$ | 12 | $10 + 4 \times 1 = 14$ | 12 | $10 + 2 \times 1 = 12$ | 12 | $23 - 8 \times 0 = 15$ |
| 13 | $13 + 15 \times 0 = 13$ | 13 | $11 + 4 \times 0 = 11$ | 13 | $13 + 2 \times 0 = 13$ | 13 | $25 - 15 \times 1 = 10$ |
| 14 | $14 + 15 \times 1 = 29$ | 14 | $11 + 4 \times 1 = 15$ | 14 | $13 + 2 \times 1 = 15$ | 14 | $27 - 15 \times 1 = 12$ |
| 15 | $15 + 15 \times 0 = 15$ | 15 | $12 + 4 \times 0 = 12$ | 15 | $14 + 2 \times 0 = 14$ | 15 | $29 - 15 \times 1 = 14$ |
| 16 | $16 + 15 \times 1 = 31$ | 16 | $12 + 4 \times 1 = 16$ | 16 | $14 + 2 \times 1 = 16$ | 16 | $31 - 15 \times 1 = 16$ |
| | | 17 | $17 + 4 \times 0 = 17$ | 17 | $17 + 2 \times 0 = 17$ | | |
| | | 18 | $17 + 4 \times 1 = 21$ | 18 | $17 + 2 \times 1 = 19$ | | |
| | | 19 | $18 + 4 \times 0 = 18$ | 19 | $18 + 2 \times 0 = 18$ | | |
| | | 20 | $18 + 4 \times 1 = 22$ | 20 | $18 + 2 \times 1 = 20$ | | |
| | | 21 | $19 + 4 \times 0 = 19$ | 21 | $21 + 2 \times 0 = 21$ | | |
| | | 22 | $19 + 4 \times 1 = 23$ | 22 | $21 + 2 \times 1 = 23$ | | |
| | | 23 | $20 + 4 \times 0 = 20$ | 23 | $22 + 2 \times 0 = 22$ | | |
| | | 24 | $20 + 4 \times 1 = 24$ | 24 | $22 + 2 \times 1 = 24$ | | |
| | | 25 | $25 + 4 \times 0 = 25$ | 25 | $25 + 2 \times 0 = 25$ | | |
| | | 26 | $25 + 4 \times 1 = 29$ | 26 | $25 + 2 \times 1 = 27$ | | |
| | | 27 | $26 + 4 \times 0 = 26$ | 27 | $26 + 2 \times 0 = 26$ | | |
| | | 28 | $26 + 4 \times 1 = 30$ | 28 | $26 + 2 \times 1 = 28$ | | |
| | | 29 | $27 + 4 \times 0 = 27$ | 29 | $29 + 2 \times 0 = 29$ | | |
| | | 30 | $27 + 4 \times 1 = 31$ | 30 | $29 + 2 \times 1 = 31$ | | |
| | | 31 | $28 + 4 \times 0 = 28$ | 31 | $30 + 2 \times 0 = 30$ | | |
| | | 32 | $28 + 4 \times 1 = 32$ | 32 | $30 + 2 \times 1 = 32$ | | |

table of an 8 × 8 DLN shows the channels' allocation in each stage, which consists of four transformation tables of the 4 × 4 DLN, eight 1 × 2 active beam splitters, and eight 2 × 1 active beam combiners. The thickness of the dielectric substrate of stages 1, 2, 3, 4, and 5 are $4t$, $2t$, $t$, $t$, and $2t$, respectively, and are labeled in Fig. 7. Figure 8 shows the transformation tables of an $N \times N$ DLN, which consists of the transformation tables of four $N/2 \times N/2$ DLNs, $N$ 1 × 2 active beam splitters of the first stage, and $N$ 2 × 1 active beam combiners of the last stage in Fig. 7. It is a recursive structure too.

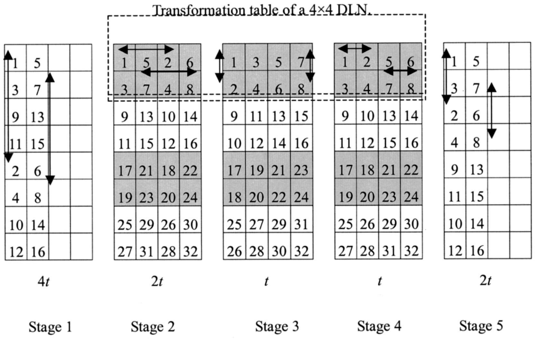

Fig. 7. Transformation table of an 8 × 8 double-layer network.

## 4. Number of Drivers

As shown in Fig. 2 for a 4 × 4 DLN, $S_{i-j}$ represents the $j$th switch in stage $i$, $I_m$ represents the input channel $m$, and $O_n$ represents output channel $n$. If

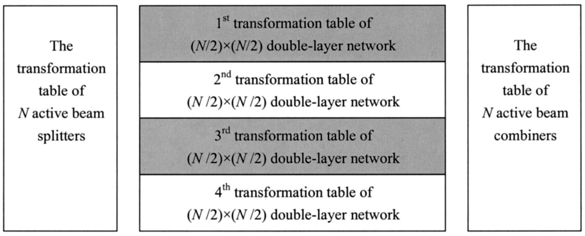

Fig. 8. Transformation table of an $N \times N$ double-layer network.

input $I_1$ is connected to output $O_3$, $S_{1\text{-}1}$ is in the swap state, which allows input $I_1$ to connect to output $O_3$ or $O_4$, and $S_{3\text{-}3}$ is in the straight state, which allows output $O_3$ to connect to output $I_1$ or $I_2$. For input $I_1$ to connect with output $O_3$, $S_{2\text{-}3}$ must be in the straight state. When input $I_2$ is connected to output $O_1$, $S_{2\text{-}1}$ is in the swap state. Because the switching states of $S_{2\text{-}1}$ and $S_{2\text{-}3}$ are different, these two switches need two individual drivers. For the same reason each switch in the innermost stage needs one driver. Because there are $N^2/4$ switches in the innermost stage, the innermost stage needs $N^2/4$ drivers.

As shown in Fig. 6 for an 8 × 8 DLN, if input $I_1$ is connected to output $O_5$, $S_{1\text{-}1}$ is in the swap state and $S_{2\text{-}9}$ is in the straight state, which allows input $I_1$ to connect to output $O_5$ or $O_6$, and $S_{4\text{-}9}$ and $S_{5\text{-}5}$ are in the straight states, which allows output $O_5$ to connect to output $I_1$ or $I_2$. For connecting input $I_1$ to output $O_5$, $S_{3\text{-}9}$ must be in the straight state. For this connection path the switching state of $S_{2\text{-}1}$ can be neglected. When $S_{2\text{-}1}$ is used (input $I_1$ is connected to output $O_1$ or $O_2$), the switching state of $S_{2\text{-}9}$ can be neglected too. Hence $S_{2\text{-}1}$ and $S_{2\text{-}9}$ can be set in the same switching state in any connecting case. Therefore these two switches need only one driver. The same situations occur in the switch pairs: $S_{2\text{-}2}$ with $S_{2\text{-}10}$, $S_{2\text{-}3}$ with $S_{2\text{-}11}, \ldots,$ and $S_{2\text{-}8}$ with $S_{2\text{-}16}$. Because there are 16 switches in stage 2 and each pair of switches needs one driver, 8 drivers are required. Hence this stage needs only 8 drivers, and this number is the same as the number of inputs and outputs. Because there are $2\log_2 N - 1$ stages (including the innermost stage) in this network, the number of drivers is

$$\begin{aligned} D_N &= D_{N\text{-inner}} + (2\log_2 N - 2) \times N, \\ &= \frac{N^2}{4} + 2N\log_2 N - 2N, \end{aligned} \tag{2}$$

where $D_{N\text{-inner}}$ is the number of drivers in the innermost stage.

To reduce the required drivers, the control configuration of switches in the innermost stage has to be adjusted. In the innermost stage each switch needs four EOHWPs, and each EOHWP can be controlled individually as shown in Fig. 9.

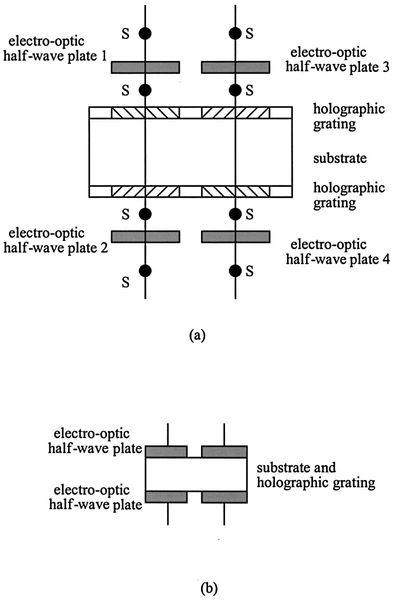

Fig. 9. (a) Holographic optical switch with four electro-optic half-wave plates to maintain optical beam polarization; (b) simplified symbol.

Figure 10 shows a 4 × 4 DLN with HOSs in which the switches in the innermost stage (stage 2) have four EOHWPs, and other switches have only two EOHWPs. If input $I_1$ is connected to output $O_3$, the EOHWP 1-1L and 1-1R are in the active states, which allows input $I_1$ to connect to output $O_3$ or $O_4$, and the EOHWP 3-3L and 3-3R are in the inactive states, which allows output $O_3$ to connect to output $I_1$ or $I_2$. For connecting input $I_1$ with output $O_3$, EOHWP 2-3L1 and 2-3R1 must be in the inactive states. For this connection path the state of EOHWP 2-1L1 can be neglected. When EOHWP2-1L1 is used (input 1 connected to output 1 or 2), the state of EOHWP2-3L1 can be neglected too. Hence EOHWP2-1L1 and 2-3L1 can be set on the same state in any connecting case. Therefore these two EOHWPs need only one driver. The same situations occur on EOHWP pairs EOHWP2-1L2 with 2-3L2, EOHWP2-2L1 with 2-4L1, and EOHWP2-2L2 with 2-4L2. Because there are 16 EOHWPs in stage 2 and each pair of EOHWPs needs one driver, 8 drivers are required.

Figure 11 shows an 8 × 8 DLN in which the same situations occur in stages 2, 3, and 4. In this net-

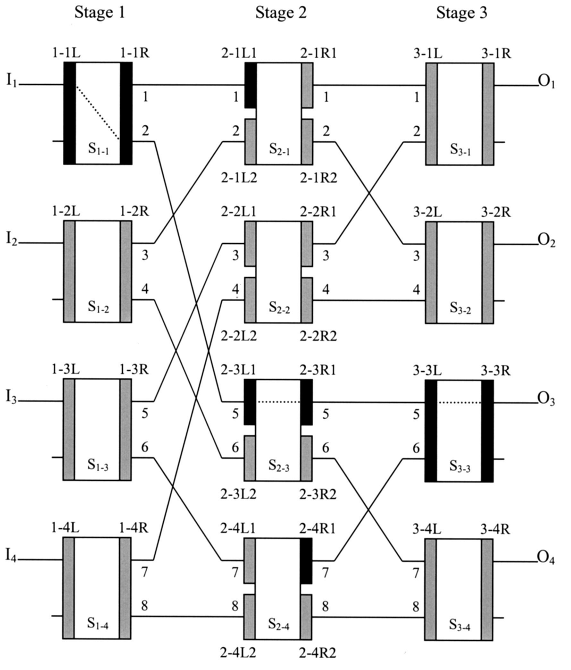

Fig. 10. A 4 × 4 double-layer network with holographic optical switches in which the switches in the innermost stage have four electro-optic halfwave plates.

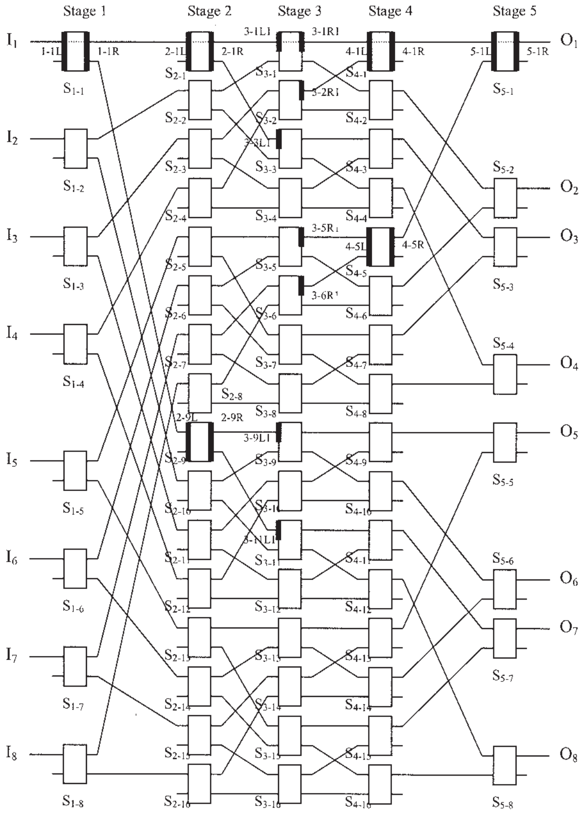

Fig. 11. An 8 × 8 double-layer network with an ordered switch and EOHWP numbers.

work, EOHWP 3-1L1, 3-3L1, 3-9L1, and 3-11L1 are in the same group, which needs one driver. Since there are 64 EOHWPs in stage 3 and each group of EOHWPs needs one driver, stage 3 needs 16 drivers.

In the innermost stage of a 4 × 4 DLN, two EOHWPs need one driver. In the innermost stage of an 8 × 8 DLN, four EOHWPs need one driver. Hence, in the innermost stage of an $N \times N$ DLN, $N/2$ EOHWPs need only one driver too. In an $N \times N$ DLN there are $N^2/4$ switches in the innermost stage. Because each switch in the innermost stage has four EOHWPs, there are $N^2$ EOHWPs. The required number of drivers is $2N$ in the innermost stage of an $N \times N$ DLN, since $N/2$ EOHWPs need one driver. As for a $2N \times 2N$ DLN the number of switches is $(2N)^2/4 = N^2$, and the corresponding number of drivers of the innermost stage ($D_{N\text{-inner}}$) is $2 \times (2N) = 4N$.

In stage 2, since there are 16 switches and each switch needs two EOHWPs, there are 32 EOHWPs in this stage. EOHWP 2-1L, 2-1R ($S_{2\text{-}1}$), 2-9L, and 2-9R ($S_{2\text{-}9}$) are in the same group, which needs one driver too. Hence this stage needs only 8 drivers, and this number is the same as the number of inputs and outputs. Because there are $2\log_2 N - 1$ stages (including the innermost stage) in this network, the number of drivers is

$$\begin{aligned} D_N &= D_{N\text{-inner}} + (2\log_2 N - 2) \times N, \\ &= 2N\log_2 N. \end{aligned} \tag{3}$$

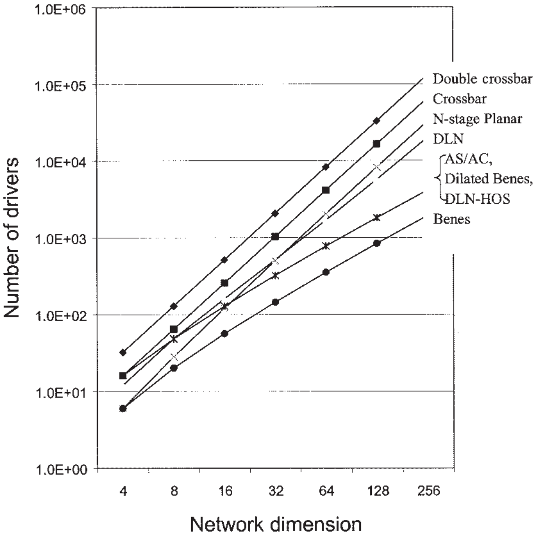

Fig. 12. Number of drivers for various networks.

Therefore the number of drivers of DLN are reduced from $N^2/4 + 2N\log_2 N - 2N$ to $2N\log_2 N$, when this network is built with HOSs. This advantageous result can be achieved only when the characteristics of the DLN and the HOS are combined. The specific characteristic of a DLN is that each switch is with only one optical beam passing through except for the switches in the innermost stage, and several switches can be controlled by one driver, which can be seen in an 8 × 8 DLN for the switch pairs $S_{2\text{-}1}$ with $S_{2\text{-}9}$, $S_{2\text{-}2}$ with $S_{2\text{-}10}$, . . . , and $S_{2\text{-}8}$ with $S_{2\text{-}16}$ shown in Fig. 6 as an example. Therefore the number of drivers can be efficiently reduced for our structure, and a similar result cannot be obtained for other networks.

The numbers of drivers for various networks are shown in Fig. 12. As shown in Fig. 12, a DLN with holographic optical switches requires the fewest drivers except for the Benes network and has the same driver numbers as the dilated double layer, AS/AC, and dilated Benes networks.

## 5. Conclusion

The double-layer network has some advantages, such as being strictly nonblocking and having a simpler routing algorithm, the lowest system insertion loss, a zero differential loss, fewer drivers, fewer crossovers, and the best SNR compared with any nondilated network. When a holographic optical switch is used to build this network, the number of required drivers is reduced from $N^2/4 + 2N\log_2 N - 2N$ to $2N\log_2 N$. After the dimension of the holographic optical switches is adjusted, all interconnection lines can be eliminated. Hence the performance of a double-layer network can be improved with holographic optical switches.

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