# Performance Improvement of Double-Layer Networks with Holographic Optical Switches 

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#### Abstract

In our previous research, combining the unique features of the double-layer network and holographic optical switches not only reduces the volume of the whole system and eliminates all interconnection lines and crossovers significantly, but also reduces the number of drivers from $N^{2} / 4+2 \operatorname{Nog}_{2} N-2 N$ to $2 \operatorname{Nog}_{2} N$. In this paper, modifying the structures of the holographic optical switches to satisfy the characteristics of the double-layer network, the system insertion loss can be minimized significantly from $\left(2 \log _{2} N-1\right)\left(L_{\mathrm{PBS}}+2 L_{\text {EOHWP }}\right)$ to $\left(2 \log _{2} N-2\right) L_{\text {PBS }}+2\left(\log _{2} N\right) L_{\text {EOHWP }}(\mathrm{dB})$. After rearranging the channels, the number of electro-optic halfwave plates can be decreased significantly from $2 N^{2}-2 N$ to $2 N \log _{2} N$.


Key-Words: - holographic optical switch, polarization beam splitter, double-layer network, optical interconnection network, system insertion loss, signal-to-noise ratio

## 1 Introduction

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, and the best signal-to-noise ratio (SNR) compared with any nondilated network [1, 2]. However, they require a large number of switches, interconnection lines, and crossovers. In our previous research, these drawbacks can be solved by using holographic optical switches (HOSs) [2].

A DLN is a recursive structure network, which consists of three stages: the right stage, the left stage, and the middle stage, as shown in Fig. 1 [1, 2]. The middle stage has four $(N / 2) \times(N / 2)$ subnetworks. In the left stage, there are $N 1 \times 2$ optical switches. The upper output channels of these optical switches in the upper layer connect to the first subnetwork and the lower output channels connect to the third subnetwork. Similarly, the second and the fourth subnetworks connect to the upper and the lower output channels of these optical switches in the lower layer, respectively. In the right stage, there are $N 2 \times 1$ optical switches. The upper and the lower input channels of these optical switches in the upper layer connect to the first and the second subnetworks, respectively, and the third and the fourth subnetworks connect to the upper and the lower input
channels of these optical switches in the lower layer, respectively. The numbers of stages of the $1 \times 2,2 \times 2$, and $2 \times 1$ optical switches are $k-1,1$, and $k-1$, respectively, where $k=\log _{2} N$. Figure 2 shows a $4 \times 4$ double layer network, which the $(N / 2) \times(N / 2)$ subnetwork is a $2 \times 2$ optical switch.


Fig. 1. The basic structure of an $N \times N$ double-layer network.


Fig. 2. A $4 \times 4$ double-layer network.

## 2 Basic Holographic Optical Switches

Conventionally, basic switching elements used in these network structures are integrated electro-optic devices on $\mathrm{Ti}: \mathrm{LiNbO}_{3}$ (titanium diffused lithium niobate) material [3] or prism polarization beam splitters (PBSs) in conjunction with electro-optic halfwave plates (EOHWPs), such as ferroelectric liquid crystals [4-5].

Integrated electro-optic devices are two-dimensional elements and all interconnection lines between switching elements are located in the same plane, which result in many crossovers for a large interconnection network [6] and cause significant insertion loss. On the other hand, these prism PBSs are bulky cube devices, which guide optical beams with different polarizations into two perpendicular directions [4-5]. To construct an optical interconnection network with these switching elements, additional mirrors are required to guide output optical beams to the succeeding switching elements.

HOSs perform polarization-dependent characteristics. With suitable designs, highly polarization-selective holographic elements can be achieved, and these components have been designed and fabricated [2, 7-27]. Utilizing flexibility and compactness features, the dimensions of the HOSs can be adjusted, which may eliminate the necessity of interconnection lines between switching elements to build many types of networks [2, 13-27]. Compared with other two types of switching elements, HOSs are more suitable for building optical interconnection networks.

In this section, $1 \times 2$ and $2 \times 2$ holographic PBSs are discussed. With EOHWPs, polarization-dependent and low-crosstalk optical switching elements are constructed. All of these devices are compact and light-weight, and the feature
of normally incident and output coupling provide better flexibility and easier alignment for system applications.

In a $1 \times 2$ holographic PBS as shown in Fig. 3, two conjugate polarization-selective holographic grating pairs are formed on two sides of a dielectric substrate. The diffraction angle in the film medium is $\theta_{\mathrm{D}}$, and the Bragg reconstruction input angle is $0^{\circ}$, i.e. the input optical beam is normally incident on the device. On the other hand, in the output coupling, the reconstruction angle is $\theta_{\mathrm{D}}$ and the output diffracted optical beam is also normal to the device as shown in Fig. 3(b). Based on Kogelnik's coupled wave theory for a volume type of grating [28], the diffraction efficiencies of $s$ - and $p$-polarization fields with respect to the grating plane, $\eta_{s}$ and $\eta_{p}$, are given as

$$
\begin{align*}
\eta_{s} & =\sin ^{2} v_{s},  \tag{1}\\
\text { and } \eta_{p} & =\sin ^{2} v_{p}, \tag{2}
\end{align*}
$$

where the modulation parameters, $v_{s}$ ( $s$-polarization) and $v_{p}$ ( $p$-polarization) are given as

$$
\begin{gather*}
v_{s}=\frac{\pi n_{\mathrm{g}} d_{\mathrm{g}}}{\lambda \sqrt{\cos \theta_{D}}},  \tag{3}\\
\text { and } v_{p}=v_{s} \cos \theta_{D}=\frac{\pi n_{\mathrm{g}} d_{\mathrm{g}} \sqrt{\cos \theta_{D}}}{\lambda}, \tag{4}
\end{gather*}
$$

respectively, where $\lambda$ is the operating wavelength, $d_{\mathrm{g}}$ is the thickness of the grating film, and $n_{\mathrm{g}}$ is the index modulation of the grating. Based on Eqs. (3) and (4), suitable value for $\theta_{\mathrm{D}}$ and $n_{\mathrm{g}} d_{\mathrm{g}} / \lambda$ can be solved, as shown in Table 1, to obtain high polarization-selective property $(0 \%$ - and $100 \%$ diffraction for $s$ - and $p$-polarization fields, respectively, or $0 \%$ - and $100 \%$-diffraction for $p$-and $s$-polarization fields, respectively), and these devices have been designed and some were fabricated [7-12]. These diffraction angles are greater than the critical angle in the dielectric substrate and the beam will be totally internal reflected. The values in Table 1 are the ideal cases. The experimental values of $\tau_{s}$ and $\eta_{p}$ are great than $90 \%$ and $\eta_{s}$ and $\tau_{p}$ are less than $3 \%$ [7].

Table 1. Parameter values of polarization-selective grating.

| $v_{s}$ | $\pi$ | $3 \pi / 2$ | $2 \pi$ |
| :--- | :--- | :--- | :--- |
| $v_{p}$ | $\pi / 2$ | $\pi$ | $3 \pi / 2$ |
| $\eta_{s}$ | $0 \%$ | $100 \%$ | $0 \%$ |
| $\eta_{p}$ | $100 \%$ | $0 \%$ | $100 \%$ |
| $\theta_{\mathrm{D}}$ <br> $\cos ^{-1}\left(v_{p} / v_{s}\right)$ | $60.0^{\circ}$ <br> $\cos ^{-1}(1 / 2)$ | $48.2^{\circ}$ <br> $\cos ^{-1}(2 / 3)$ | $41.4^{\circ}$ <br> $\cos ^{-1}(3 / 4)$ |
| $n_{\mathrm{g}} d_{\mathrm{g}} / \lambda$ | 0.707 | 1.22 | 1.73 |


(b)

Fig. 3. $1 \times 2$ holographic PBS where $\mathrm{HG}_{\mathrm{I}}, \mathrm{HG}_{\mathrm{O}}, d_{\mathrm{c}}$, and $t_{\text {sub }}$ are input holographic grating, output holographic grating, distance between two output channels, and the corresponding thickness of the dielectric substrate respectively.

Using $s$-transmission $/ p$-diffraction gratings in the structure shown in Fig. 3(a) as an example, when the input optical beam is $s$-polarized, the direction of this optical beam will not be changed by the input coupling holographic grating $\left(\mathrm{HG}_{\mathrm{I}}\right)$. This device performs the function of "straight" connection (direct transmission). Similarly, the $s$-polarized optical beam from the original output channel will follow the same path backward and finally reach the original input channel. On the other hand, when the input optical beam is $p$-polarized, the input optical beam is diffracted by $\mathrm{HG}_{\mathrm{I}}$ and normally coupled out with a conjugate diffraction by the output coupling holographic grating $\left(\mathrm{HG}_{\mathrm{o}}\right)$. This device performs the function of "turn" connection (diffraction) as shown in Fig. 3(b). The backward $p$-polarized optical beam will pass the same path from the original output channel to the original input channel. As shown in Fig. 3(a) and 3(b), these two output optical beams and the input optical beam have the same propagation direction. Obviously, this $1 \times 2$ holographic PBS provides a switching function for bi-directional connection. Therefore, this $1 \times 2$ holographic PBS can also function as a $2 \times 1$ holographic beam combiner.

The structure of a $2 \times 2$ holographic PBS is shown in Fig. 4. In this structure, two symmetric polarization-selective holographic grating pairs are formed on two sides of a dielectric substrate. Using $s$-transmission/p-diffraction gratings in the structure shown in Fig. 4(a) as an example, when the input optical beams are $s$-polarized, the direction of these optical beams will not be changed by $\mathrm{HG}_{\mathrm{I}}$ and $\mathrm{HG}_{\mathrm{o}}$. The device will perform the function of "straight" connections (direct transmission). On the other hand, when the input optical beams are $p$-polarized, the input optical beams are diffracted by $\mathrm{HG}_{\mathrm{I}}$ and normally coupled out with a conjugate diffraction by $\mathrm{HG}_{\mathrm{o}}$. The device will perform the function of "swap" connections (diffraction) as shown in Fig. 4(b). Similarly, the $2 \times 2$ holographic PBS is a bi-directional device. The optical beam at the original output channel will propagate backward through the path of forward optical beam to the original input channel.


Fig. 4. $2 \times 2$ holographic PBS: (a) the "straight" state; (b) the "swap" state.

In the $2 \times 2$ holographic PBS and the $1 \times 2$ holographic PBS, the distance between two output channels is $d_{\mathrm{c}}$ and the corresponding thickness of the dielectric substrate is $t_{\text {sub }}$. The relation between these two parameters is

$$
\begin{equation*}
t_{\mathrm{sub}}=d_{\mathrm{c}} \times \cot \theta_{\mathrm{D}} . \tag{5}
\end{equation*}
$$

In other words, when the distances between these two output channels in the $2 \times 2$ holographic PBS and the $1 \times 2$ switching element are changed to $2 d_{\mathrm{c}}$, the corresponding thickness of the dielectric substrates become $2 t_{\text {sub }}$.

A basic $1 \times 2$ HOS consists of an $1 \times 2$ holographic PBS and two EOHWPs as shown in Fig. 5. The initial input and final output optical beams are $s$-polarized as shown in these figures. The optical paths of the signal and noise in a $1 \times 2$ HOS is shown in Fig. 5. When EOHWPs are inactive, the optical beam keeps $s$-polarization, and directly passes these two EOHWPs and holographic PBS. The $1 \times 2$ HOS provides "straight" function as shown in Fig. 5(a), where input channel connects to output channel $\mathrm{O}_{1}$. In this case, the signal and noise powers at $\mathrm{O}_{1}$ and $\mathrm{O}_{2}$ are $(1-\varepsilon) P_{\text {in }}$ and $\varepsilon P_{\text {in }}$, respectively, and the contrast ratio (CR) is $(1-\varepsilon) P_{\text {in }} / \varepsilon P_{\text {in }} \cong 1 / \varepsilon$, where $\varepsilon$ is the crosstalk of the holographic PBS.


Fig. 5. The crosstalk in a $1 \times 2$ HOS: (a) "straight" state and (b) "turn" state, where HG and EOHWP are holographic grating and electro-optic halfwave plate. In these two figures, the wide solid, narrow solid, wide dash, and narrow lines are presented the $s$-polarized signal path, $s$-polarized noise path, $p$-polarized signal path, and $p$-polarized noise path, respectively.

When EOHWPs are active, the $s$-polarized input optical beam becomes $p$-polarized after passing through the first EOHWP. The propagation direction of this $p$-polarized optical beam will be turned to $\mathrm{O}_{2}$ by the holographic PBS. And then, its polarization will be turned back to $s$-polarization by the second EOHWP. In this situation, the $1 \times 2$ HOS provides "turn" function as shown in Fig. 5(b), and the signal and noise powers at $\mathrm{O}_{2}$ and $\mathrm{O}_{1}$ are $(1-\varepsilon) P_{\mathrm{in}}$ and $\varepsilon P_{\mathrm{in}}$, respectively, and the CR is $1 / \varepsilon$, too.

Also, the optical beams from the output channels can follow the same paths backward with corresponding polarization and finally reach the input channel. Obviously, this $1 \times 2$ HOS provides bi-directional switching function. Therefore, a $1 \times 2$ HOS can act as a $2 \times 1$ HOS.

A basic $2 \times 2$ HOS consists of two EOHWPs and one $2 \times 2$ holographic PBS as shown in Fig. 6. Because the structure of this basic $2 \times 2$ HOS is symmetric, it provides a bi-directional switching function. When EOHWPs are inactive, the polarizations of two input optical beams are not changed. The direction of these optical beams will not be changed by the holographic PBS. At this time, input channels $I_{1}$ and $I_{2}$ connect to output channels $O_{1}$ and $\mathrm{O}_{2}$, respectively, and it provides "straight" connection as shown in Fig. 6(a). In this case, the signal and noise powers from desired and undesired channels to output channels are $(1-\varepsilon) P_{\text {in }}$ and $\varepsilon P_{\text {in }}$, respectively, and the CR is $1 / \varepsilon$.

When EOHWPs are active, these two optical beams polarization orientations are rotated by $90^{\circ}$ and the polarization of these two optical beams are $p$-polarized. The transmission directions of these two optical beams have been swapped by the holographic PBS. Therefore, input channels $\mathrm{I}_{1}$ and $\mathrm{I}_{2}$ connect to output channels $\mathrm{O}_{2}$ and $\mathrm{O}_{1}$, respectively. In this case, the $2 \times 2$ HOS provides "swap" connection as shown in Fig. 6(b). The same as the previous case, the signal and noise powers from desired and undesired channels are $(1-\varepsilon) P_{\text {in }}$ and $\varepsilon P_{\text {in }}$, respectively, and the CR is $1 / \varepsilon$, too.

In a double-layer network, the left, innermost, and right stages are $1 \times 2,2 \times 2$, and $2 \times 1$ optical switches, respectively. Each kind of the basic HOS is composed of a holographic PBS and two EOHWPs, and the holographic PBS was sandwiched between two EOHWPs. To maintain the optical beam at the output to have the same polarization state as that at the input, these HOSs need two EOHWPs, which can be controlled by one driver. An $N \times N$ DLN requires $1.25 N^{2}-2 N$ optical switches [1]. Therefore, it needs $2.5 N^{2}-4 N$ EOHWPs. The insertion loss of an HOS is
$L_{\text {PBS }}+2 L_{\text {EOHWP }}(\mathrm{dB})$, where $L_{\text {PBS }}$ and $L_{\text {EOHWP }}$ are the insertion losses of the holographic PBS and the EOHWP in dB, respectively. Due to these HOSs having the same insertion loss, the system insertion loss in a $N \times N$ DLN is $(2 k-1)\left(L_{\text {PBS }}+2 L_{\text {EOнWP }}\right)(\mathrm{dB})$.


Fig. 6. The crosstalk in a $2 \times 2$ HOS: (a) "straight" state and (b) "swap" state.

## 3 Modified Holographic Optical Switches

Figure 7 shows the modified $2 \times 2$ HOS, which the control configuration has been changed. This switch needs four EOHWPs and each EOHWP requires an individual driver. The innermost stage of a DLN with this modified $2 \times 2$ HOS to reduce the number of drivers has been proved and proposed in our previous research [2]. The total number of drivers in an $N \times N$ DLN can be reduced from $N^{2} / 4+2 k N-2 N$ to $2 k N$. Because the innermost stage has $N^{2} / 42 \times 2$ optical switches [1, 2] in an $N \times N$ DLN, the number of EOHWPs at the innermost stage with this modified $2 \times 2$ HOS is $N^{2}$. The insertion loss of this modified $2 \times 2$ HOS is the same as the basic $2 \times 2$ HOS because each connection path consists two EOHWPs and one holographic PBS, too.


Fig. 7. A $2 \times 2$ HOS with four EOHWPs to maintain optical beam polarization.

By the unique features of the DLN, the structure of $1 \times 2$ HOS can be modified as shown in Fig. 8, which consists of one $1 \times 2$ holographic PBS and one EOHWP. Its insertion loss has been reduced from $L_{\text {PBS }}+2 L_{\text {EOHWP }}$ to $L_{\text {PBS }}+L_{\text {EOHWP }}(\mathrm{dB})$. All of the switching situations are shown in Fig. 8. In Figs. 8(a) and $8(b)$, the input optical beams are $s$-polarized and in Figs. 8(c) and 8(d), the input optical beams are $p$-polarized. In Fig. 8(a), an $s$-polarized input optical beam passes directly through the inactive EOHWP and the dielectric substrate. In Fig. 8(d), the input optical beam is $p$-polarized and the EOHWP is active. After passing through the EOHWP, the polarization of the optical beam is rotated by $90^{\circ}$ and is $s$-polarized. In this situation, this optical beam can directly pass through the dielectric substrate. Therefore, both of Figs. 8(a) and 8(d) provide the "straight" state and the output optical beams are $s$-polarized. In these two cases, the optical power are $(1-\varepsilon) P_{\text {in }}$ and $\varepsilon P_{\text {in }}$ at the desired and undesired output channels ( $\mathrm{O}_{1}$ and $\mathrm{O}_{2}$ ), respectively.

In Fig. 8(b), the EOHWP is active. While the input optical beam passing through the EOHWP, the polarization of the optical beam is rotated by $90^{\circ}$ and is $p$-polarized. This input optical beam is diffracted by the input coupling holographic grating $\left(\mathrm{HG}_{\mathrm{I}}\right)$ and normally coupled out with a conjugate diffraction by the output coupling holographic grating $\left(\mathrm{HG}_{\mathrm{o}}\right)$. In Fig. 8(c), the input optical beam is $p$-polarized and the EOHWP is inactive. In the dielectric substrate, this input optical beam will follow the same path to output as Fig. 8(b). Hence, both of Figs. 8(b) and 8(c) provide the "turn" state and the output optical beams are $p$-polarized. In these two situations, the optical power are $(1-\varepsilon) P_{\text {in }}$ and $\varepsilon P_{\text {in }}$ at the desired and undesired output channels ( $\mathrm{O}_{2}$ and $\mathrm{O}_{1}$ ), respectively.

All of these four switching functions, the optical beams from the output channels can follow the same paths backward with corresponding polarizations and
finally reach the input channel. Obviously, this $1 \times 2$ HOS provides bi-directional switching function. Therefore, a $1 \times 2$ HOS can act as a $2 \times 1$ HOS.


Fig. 8. A simplified $1 \times 2$ HOS consists of a holographic PBS and an electro-optic halfwave plate; (a) "straight" state for $s$-polarized input, (b) "turn" state for $s$-polarized input, (c) "turn" state for p-polarized input, and (d) "straight" state for $p$-polarized input.

In an $N \times N$ DLN, the numbers of the $1 \times 2,2 \times 1$ and $2 \times 2$ HOSs are $N(N / 2-1), N(N / 2-1)$, and $N^{2} / 4$, respectively, and each connection path has $(k-1) 1 \times 2$ HOSs, one $2 \times 2$ HOS, and ( $k-1$ ) $2 \times 1$ HOSs. Because each $1 \times 2$ and $2 \times 1$ HOS has been reduced one EOHWP, the system insertion loss can be decreased from $(2 k-1)\left(L_{\mathrm{PBS}}+2 L_{\mathrm{EOHWP}}\right)$ to $(2 k-2) L_{\mathrm{PBS}}+2 k L_{\mathrm{EOHWP}}$ $(\mathrm{dB})$. Therefore, the insertion loss can be reduced efficiently by using these modified HOSs to construct a DLN.

## 4 Signal-to-Noise Ratio Analysis

The major advantage of a DLN is that it provides higher signal-to-noise ratio (SNR) than other non-dilated networks. After using these modified HOSs to construct a DLN, its system insertion loss and number of EOHWPs can be reduced. Its SNR will be reduced from $|X|-$ to $|X|-3(\mathrm{~dB})$, where $X=$ $10 \log _{10}(\varepsilon)$ is the crosstalk in dB . This phenomenon is shown in Fig. 9. In this case, input channels $\mathrm{I}_{1}, \mathrm{I}_{2}, \mathrm{I}_{3}$, and $\mathrm{I}_{4}$ connect to output channels $\mathrm{O}_{1}, \mathrm{O}_{2}, \mathrm{O}_{4}$, and $\mathrm{O}_{3}$, respectively. At output channel $\mathrm{O}_{1}$, the signal is from input channel $\mathrm{I}_{1}$ and its power is $(1-\varepsilon)^{3} P_{\text {in }}$ with $s$-polarization. The noise power from input channel $\mathrm{I}_{2}$, $\mathrm{I}_{3}$, and $\mathrm{I}_{4}$ are $\varepsilon(1-\varepsilon)^{2} P_{\text {in }}, \varepsilon^{2}(1-\varepsilon) P_{\text {in }}$, and $\varepsilon(1-\varepsilon)^{2} P_{\text {in }}$ and their corresponding polarization are $s$-, $p-$, and $p$-polarization, respectively. The major items of the noises at output channel $\mathrm{O}_{1}$ are two different polarized first order crosstalk and its total power is $2 \varepsilon(1-\varepsilon)^{2} P_{\text {in }}$. The other item from input channel $\mathrm{I}_{3}$ is a high order noise $\left(\varepsilon^{2}(1-\varepsilon) P_{\text {in }}\right)$ and it can be neglected. In this case, its $\mathrm{SNR}=10 \log _{10}\left[(1-\varepsilon)^{3} \operatorname{Pin} / 2 \varepsilon(1-\varepsilon)^{2} P \mathrm{in}\right]$ $\cong 10 \log _{10}(1 / 2 \varepsilon)=|X|-3(\mathrm{~dB})$. Therefore, the SNR has been reduced. Because the polarizations of the signal and one of the first order noise are different, this noise item can be cancelled by cascaded a polarizer as shown in Fig. 10. After canceling the first order $p$-polarized noise, the SNR will be recovered from $|X|-3$ to $|X|$. With the same reason, the SNR can be keep at $|X|$ in an $N \times N$ network.


Fig. 9. A $4 \times 4$ DLN with modified HOSs. This connection state has the worst SNR.

## 5 DDLN with Modified HOSs

To increase the SNR of a DLN, its innermost $2 \times 2$ optical switches have to be dilated [1]. The network structure is called dilated double-layer network (DDLN) and its SNR can be increased to
$2|X|-10 \log _{10}(k)(\mathrm{dB})$. In an $N \times N$ DDLN, it requires $2 N^{2}-2 N$ optical switches and each connection path has $2 k$-stage of optical switches [1]. When use the basic HOSs to construct the DDLN, the numbers of holographic PBSs and EOHWPs it needed are $2 N^{2}-2 N$ and $4 N^{2}-4 N$, respectively, and the system insertion loss is $2 k\left(L_{\text {PBS }}+2 L_{\text {EOHWP }}\right)(\mathrm{dB})$. Figure 11 shows a $4 \times 4$ DDLN with basic HOSs. In this structure, there are 24 HOSs. Each HOS consists of one holographic PBS and two EOHWPs and its system insertion loss is $4\left(L_{\mathrm{PBS}}+2 L_{\mathrm{EOHWP}}\right)$.


Fig. 10. A $4 \times 4$ DLN with modified HOSs. This connection state has the worst SNR.


Fig. 11. A $4 \times 4$ DDLN with basic HOSs.
Figure 12 shows a $4 \times 4$ DDLN with these modified HOSs, which the $2 \times 2$ holographic PBSs at the innermost stage have been dilated. In this structure, there are 24 holographic PBSs, too, but the number of the EOHWPs has been reduced from 48 to
24. Because each HOS has been modified which consists of one holographic PBS and one EOHWP, the system insertion loss has been reduced from $4\left(L_{\text {PBS }}+2 L_{\text {EOHWP }}\right)$ to $4\left(L_{\text {PBS }}+L_{\text {EOHWP }}\right)$. Extending to $N \times N$, both of the number of holographic PBSs and EOHWPs are $2 N^{2}-2 N$. The number of the EOHWPs has been decreased and the system insertion loss has been reduced from $2 k\left(L_{\mathrm{PBS}}+2 L_{\mathrm{EOHWP}}\right)$ to $2 k\left(L_{\mathrm{PBS}}+L_{\text {EOHWP }}\right)(\mathrm{dB})$.


Fig. 12. A $4 \times 4$ DDLN with these modified HOSs. This connection state has the worst SNR.

In the same connection state as Fig. 9, input channels $\mathrm{I}_{1}, \mathrm{I}_{2}, \mathrm{I}_{3}$, and $\mathrm{I}_{4}$ connect to output channels $\mathrm{O}_{1}, \mathrm{O}_{2}, \mathrm{O}_{4}$, and $\mathrm{O}_{3}$, respectively. At output channel $\mathrm{O}_{1}$, the signal is from input channel $\mathrm{I}_{1}$ and its power is $(1-\varepsilon)^{4} P_{\text {in }}$ with $s$-polarization. The noise powers from input channel $\mathrm{I}_{2}, \mathrm{I}_{3}$, and $\mathrm{I}_{4}$ are $\varepsilon^{2}(1-\varepsilon)^{2} P_{\mathrm{in}}, \varepsilon^{3}(1-\varepsilon) P_{\text {in }}$, and $\varepsilon(1-\varepsilon)^{3} P_{\text {in }}$ and their corresponding polarization are $s$-, $p$-, and $p$-polarization, respectively. The major item of the noise at output channel $\mathrm{O}_{1}$ is the first order crosstalk and its power is $\varepsilon(1-\varepsilon)^{3} P_{\text {in }}$, which is from $\mathrm{I}_{4}$. The other items from input channels $\mathrm{I}_{2}$ and $\mathrm{I}_{3}$ are high order noises $\left(\varepsilon^{2}(1-\varepsilon)^{2} P_{\text {in }}\right.$ and $\varepsilon^{3}(1-\varepsilon) P_{\text {in }}$, respectively) and they can be neglected. In this case, its $\mathrm{SNR}=10 \log _{10}\left[(1-\varepsilon)^{4} \operatorname{Pin} / \varepsilon(1-\varepsilon)^{3} \operatorname{Pin}\right] \cong 10 \log _{10}(1 / \varepsilon)$ $=|X|(\mathrm{dB})$. Therefore, the SNR has been reduced from $2|X|-10 \log _{10}(k)$ to $|X| \quad(\mathrm{dB})$. Due to that the polarizations of the signal and the first order noise are different, this noise item can be cancelled by cascaded a polarizer as shown in Fig. 13.

Figure 13 shows the worst case of SNR of a $4 \times 4$ DDLN which cascades polarizer to cancel the first order $p$-polarized noise. In this figure, input channels $\mathrm{I}_{1}, \mathrm{I}_{2}, \mathrm{I}_{3}$, and $\mathrm{I}_{4}$ connect to output channels $\mathrm{O}_{1}, \mathrm{O}_{2}, \mathrm{O}_{3}$, and $\mathrm{O}_{4}$, respectively. At output channel $\mathrm{O}_{1}$, the signal
is from input channel $\mathrm{I}_{1}$ and its power is $(1-\varepsilon)^{4} P_{\text {in }}$. The noise powers from input channel $\mathrm{I}_{2}, \mathrm{I}_{3}$, and $\mathrm{I}_{4}$ are $\varepsilon^{2}(1-\varepsilon)^{2} P_{\text {in }}, \varepsilon^{2}(1-\varepsilon)^{2} P_{\mathrm{in}}$, and $\varepsilon^{4} P_{\mathrm{in}}$, respectively. All of the signal and noise powers are $s$-polarized. The major items of the noises at output channel $\mathrm{O}_{1}$ are from $\mathrm{I}_{2}$ and $\mathrm{I}_{3}$ and both of their powers are $\varepsilon^{2}(1-\varepsilon)^{2} P_{\text {in }}$. The other item from input channel $\mathrm{I}_{4}$ are high order noise ( $\varepsilon^{4} P_{\text {in }}$ ) and it can be canceled. In this case, its SNR $=10 \log _{10}\left[(1-\varepsilon)^{4} P \mathrm{in} / 2 \varepsilon^{2}(1-\varepsilon)^{2} P \mathrm{in}\right] \cong$ $10 \log _{10}\left(1 / 2 \varepsilon^{2}\right)=2|X|-10 \log _{10}(2)(\mathrm{dB})$. After DDLN extending to $N \times N$, the SNR can be recovered to $2|X|-10 \log _{10}(k)(\mathrm{dB})$.


Fig. 13. A $4 \times 4$ DDLN constructed with modified HOSs and cascaded polarizers. This connection has the worst SNR.

## 6 Components Reduction

The numbers of the $1 \times 2,2 \times 2$, and $2 \times 1$ optical switches in the left part, the innermost stage, and right part of an $N \times N$ DLN are $N^{2} / 2-N, N^{2} / 4$, and $N^{2} / 2-N$, respectively. Each input channel connects to $N / 2-1$ optical switches, which are arranged in a ( $k-1$ )-stage complete binary tree. While these optical switches are allocated adjacent, the number of optical switches will be reduced from $N / 2-1$ to $k-1$. Fig. 14 shows the component reduction method. This method has been used to reduce the number of EOHWPs of AS/AC network from $2 N^{2}-2 N$ to $2 k N$ [26]. Due to that the structures of DDLN and AS/AC networks are equivalent, the number of EOHWPs of DDLN can be reduced from $2 N^{2}-2 N$ to $2 k N$ by using this method.

A $1 \times 4$ active splitter with HOSs consists of three $1 \times 2$ HOSs as shown in Fig. 14(a). Because only one
optical beam passes through this $1 \times 4$ active splitter, two $1 \times 2$ HOSs at Stage 2 can be driven by one driver; therefore, only need one EOHWP. Because these two $1 \times 2$ HOSs are adjacent, these two holographic PBSs can be combined together into one holographic PBS as shown in Fig. 14(b). According to the switching states of these two HOSs, the connection path in the $1 \times 4$ active splitters can be determined as shown in Table 2. While these two stages of HOSs are in "straight" state, the input connects to $\mathrm{O}_{1}$ and it is $s$-polarized at output channel. If Stage 1 is in "straight" state and Stage 2 is in "turn" state, the input is connected to $\mathrm{O}_{2}$ and the output optical beam is $p$-polarized. In the opposite case, Stage 1 is in "turn" state and Stage 2 is in "straight" state, the input is connected to $\mathrm{O}_{3}$ and the output optical beam is $s$-polarized. At the last case, the input connects to $\mathrm{O}_{4}$ and the output optical beam is $p$-polarized. Both of these two stages of HOSs are in "turn" state.

Also, the optical signal from the output channel can follow the same path backward with corresponding polarization and finally reach the input channel. Obviously, this $1 \times 4$ HOS provides bi-directional switching function. Therefore, a $1 \times 4$ HOS can act as a $4 \times 1$ HOS. Because each output channel connects to ( $N / 2-1$ ) $2 \times 1$ optical switches and they are arranged in a ( $k-1$ )-stage complete binary tree, the number of optical switches will be reduced from $N / 2-1$ to $k-1$, too.


Fig. 14. (a) $1 \times 4$ active splitter with three simplified $1 \times 2$ HOSs; (b) a compact structure of $1 \times 4$ active splitter with two simplified $1 \times 2$ HOSs.

Table 2 The switching states of HOSs of the $1 \times 4$ active splitters.

| Output <br> Cannel | HOS Switching State |  | Polarization of <br> the Output <br> Optical Beam |
| :---: | :---: | :---: | :---: |
|  | Stage 1 | Stage 2 |  |
| $\mathrm{O}_{1}$ | Straight | Straight | -polarized |
| $\mathrm{O}_{2}$ | Straight | Turn | $p$-pari |
| $\mathrm{O}_{3}$ | Turn | Straight | $s$-polarized |
| $\mathrm{O}_{4}$ | Turn | Turn | $p$-polarized |

Figure 15 shows a $4 \times 4$ DLN with modified HOSs. In the second stage of EOHWPs, the EOHWPs at channels 1 and 5 connect to the same input channel $\mathrm{I}_{1}$. These two EOHWPs only pass one optical signal at the same time. And then, these two EOHWPs can be controlled by the same driver circuit. All of the EOHWP pairs $(2,6),(3,7)$, and $(4,8)$ in the second stage of EOHWPs and $(1,3),(2,4),(5,7)$, and $(6,8)$ in the third stage of EOHWPs have the same situation. In these tow stage of EOHWPs, the number of drivers is four. By the same reason, the number of drivers of an $N \times N$ double-layer network can be reduced from $N^{2} / 4+2 k N-2 N$ to $2 k N$ [2].


Fig. 15. $4 \times 4 \mathrm{DLN}$ with modified HOSs.
The channels connection tables of the HOSs and EOHWPs of a $4 \times 4$ DLN with modified HOSs are shown in Table 3 and Table 4, respectively. Table 4 shows the allocation of EOHWPs, which is derived from Table1. Due to the innermost stage of HOSs consisting of two stages of EOHWPs, the second and third stages of EOHWPs have the same channels allocation, which is the same as the channels allocation of the second stage of HOSs in Table 3. In the third stage of EOHWPs, the EOHWPs on channels 1 and 3 can be controlled by the same driver and they are adjacent. Therefore, these two EOHWPs can be combined to one and so do the EOHWP pairs
$(2,4),(5,7)$, and $(6,8)$. Hence, the required EOHWPs have been reduced by half.

Table 3. The channels connection table of the HOSs in a $4 \times 4$ double-layer network, where $2 t_{\text {sub }}, t_{\text {sub }}$, and $2 t_{\text {sub }}$ are the corresponding thicknesses of the dielectric substrates in the first, second, and third stages of HOSs, respectively.

| $\begin{array}{c}\text { HOSs } \\ 1^{\text {st }} \\ \text { stage }\end{array}$ |  |  |  |
| :---: | :---: | :---: | :---: |
| 1 | 5 | 2 | 6 |
| 3 | 7 | 4 | 8 |

$2 t_{\text {sub }}$

| HOSs |  |  |  |
| :---: | :---: | :---: | :---: |
| $2^{\text {nd }}$ | stage |  |  |
| 1 | 3 | 5 | 7 |
| 2 | 4 | 6 | 8 |

$t_{\text {sub }}$

Table 4. The channels connection table of the EOHWPs in a $4 \times 4$ double-layer network, where dash circles are the corresponding EOHWPs.

| EOHWP |  |  |  |
| :---: | :---: | :---: | :---: |
| $1^{\text {st }}$ stage |  |  |  |
| 1 | 5 | 2 | 6 |
| $3:$ | 7 | 4 | 8 |
|  |  | 7 |  |


| EOHWP <br> $2^{\text {nd }}$ stage |  |  |  |
| :---: | :---: | :---: | :---: |
| 11 | 3 | $\stackrel{\text { ¢\% }}{ }$ | 7 |
| 2 | 4 | 6 | 8 |


| EOHWP   <br> $3^{\text {rd }}$  stage |  |  |
| :---: | :---: | :---: |
| 1 | 3 | 5 |
| 2 | 4 | 6 |


| EOHWP <br> 4 <br> th <br> atae |  |  |  |
| :---: | :---: | :---: | :---: |
| $1:$ | 2 | 5 | 6 |
| $3:$ | 4 | 7 | 8 |

However, the number of EOHWPs in the second stage can not be reduced. In this stage, channels 1 and 5 are not adjacent but are controlled by the same driver. These two EOHWPs can not be joined together. The required EOHWPs can not be reduced as the third stage. To solve this problem, the channels allocation of the HOSs and EOHWPs have to be rearranged as shown in Table 5 and Table 6, respectively. In Table 6, the third stage of EOHWPs keeps the same characteristic and the required EOHWPs can be reduced by half, too. In the second stage, channels 1 and 5 are adjacent and the EOHWPs on these two channels can be combined together, too. Therefore, the number of EOHWPs in the second stage can be reduced by half. In this $4 \times 4$ DLN, there are four stages of EOHWPS and each stage has four EOHWPs. The total number of EOHWPs is sixteen.

Table 5. The new channels connection table of the HOSs in a $4 \times 4$ double-layer network, where $2 t_{\text {sub }}$, $\sqrt{2} t_{\text {sub }}$, and $2 t_{\text {sub }}$ are the corresponding thicknesses of the dielectric substrates in the first, second, and third stages of HOSs, respectively.

$2 t_{\text {sub }}$

$\sqrt{2} t_{\text {sub }}$

$2 t_{\text {sub }}$

Table 6. The new channels connection table of the EOHWPs in a $4 \times 4$ double-layer network, where dash circles are the corresponding EOHWPs.


Figure 16 shows an $8 \times 8$ double-layer network with modified HOSs and its channels connection table of EOHWPs is shown in Table 7. An example, the channels 1 and 17 at the second stage and the channels $1,5,17$, and 21 at the third stage connect to the input channel $I_{1}$. At the second stage of EOHWPs, the EOHWPs on channels 1 and 17 can be controlled by the same driver, so do the EOHWPs on channels 1, 5, 17, and 21 at the third stage of EOHWPs. As shown in Table 7, EOHWPs on channels 1 and 17 at the second stage of EOHWPs are adjacent due to that the channel 2 does not pass optical signal and it can be neglected. These two EOHWPs can be joined together. Because the EOHWPs on channels 1, 5, 17, and 21 at the third stage of EOHWPs are adjacent, these four EOHWPs can be combined together, too. Therefore, the numbers of EOHWPs can be reduced by half and three fourths in the second and third EOHWPs, respectively.

In figure 16, there are sixteen and thirty two EOHWPs in the second and third stages of EOHWPs, respectively. Hence, both of the numbers of EOHWPs of these two stages can be reduced to eight. Because the fourth and fifth stages of EOHWPs have the same situation, their number of EOHWPs can be reduced to eight, too. Due to an $8 \times 8$ DLN with modified HOSs having six stages of EOHWPs and each stage having eight EOHWPs, its total number of EOHWPs is forty eight. Therefore, there are $N$ EOHWPs in $2 k$ stages and its total number of EOHWPs is $2 k N$ in an $N \times N$ double-layer network with modified HOSs. The number of EOHWPs has been significantly reduced from $2 N^{2}-2 N$ to $2 k N$.

## 7 Conclusions

In this paper, using holographic optical switches to build the double-layer and dilated double-layer networks have been proposed. According to the
characteristics of network, the structure of the holographic optical switch has been modified. The system insertion loss is decreased significantly from $\left(2 \log _{2} N-1\right) L_{\mathrm{PBS}}+\left(4 \log _{2} N-2\right) L_{\mathrm{EOHWP}}$ to $\left(2 \log _{2} N-2\right) L_{\text {PBS }}+2\left(\log _{2} N\right) L_{\text {EOHWP }}(\mathrm{dB})$. In the dilated double-layer network, the system insertion loss is reduced from $2 \log _{2} N\left(L_{\mathrm{PBS}}+2 L_{\mathrm{EOHWP}}\right)$ to $2 \log _{2} N\left(L_{\mathrm{PBS}}+L_{\mathrm{EOHWP}}\right) \quad(\mathrm{dB})$. Therefore, this modification results that the insertion loss can be reduced efficiently. Finally, the system signal-to-noise ratio can keep at the original value by cascaded polarizer. After rearranging the channels of the double-layer network with holographic optical switches, its number of electro-optic halfwave plates can be decreased significantly from $5 N^{2} / 2-4 N$ to $2 \mathrm{Nlog}_{2} \mathrm{~N}$.


Fig. 16. An $8 \times 8$ DLN with modified HOSs.

Table 7. The new channels connection table of the EOHWPs in an $8 \times 8$ double-layer network, where dash circles are the corresponding EOHWPs.

| EOHWPs |  |  |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 1 |  | 5 |  | 9 |  | 13 |  |
|  | 3 |  | 7 |  | 1 |  | 15 |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
| 2 |  | 6 |  | 10 |  | 14 |  |
|  | 4 |  | 8 |  | 12 |  | 16 |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |


| EOHWPs <br> $2^{\text {nd }}$ stage |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1: | $\therefore$ | \% | $\because$ | 9 |  | 13: | $\because$ |
|  | 3 |  | 7 |  | 11 |  | 15 |
| $\vdots$ |  | 6 |  | 10 |  | 14: |  |
|  | 4 |  | 8 |  | 12 ! |  | 16 |
| 17: ${ }^{\text {: }}$ |  | $2{ }^{2}$ |  | $25:$ |  | 2.9 |  |
|  | 1i9: |  | 23: |  | 27 |  | 31 |
| 18 |  | 22 |  | 26 |  | 30 |  |
|  | 20 |  | 24 |  | 28 |  | 32 |


| EOHWPs <br> $3^{\text {rd }}$ stage |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1: |  | :3 |  | $\because 9$ |  | 111 |  |
|  | 2 | $\vdots$ | 4 |  | 10 |  | 12 |
| 5 |  | 7 |  | :13: |  | 15 | $\vdots$ |
|  | 6 |  | 8 |  | 14 |  | 16 |
| 17 |  | 9: |  | 25 ! |  | 27 |  |
|  | 18 : | ! | $20 \vdots$ |  | 26 |  | 28 |
| 2.1 |  | 23 |  | 29 |  | 31 | : |
|  | 2.2 |  | 24 |  | 30 |  | 32 |


| $\begin{aligned} & \text { EOHWPs } \\ & 4^{\text {th }} \text { stage } \end{aligned}$ |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\because$ | ..... | . 3. | ...... | 9.. |  | ijp |  |
|  | $2 \cdots$ |  | 4 |  | 10 |  | 12: |
| $\because$ |  | 7. |  | 13. | ...... | $15 \%$ |  |
|  | . 6. |  | 8. |  | 14 |  | 16: |
| 17\%. | ..... | 19 |  | 25. |  | 2.7 |  |
|  | 18\%. |  | 20 |  | 26. |  | 28 |
| $2 \cdots$ |  | 23 |  | 29 |  | 31 |  |
|  | 22. | ....... | 24. |  | $30 .$. | ....... | 32 |


| EOHWPs <br> $5^{\text {th }}$ stage |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 |  | .2... |  | . $9 \cdot$ |  | 10 |  |  |
|  | 3 |  | 4. |  | $4{ }^{\circ}$ |  | 12 |  |
| $5 \%$ | ..... | 6. |  | 13. |  | 14 |  |  |
|  | 7 |  | .8.:. |  | 15 |  | 16 |  |
| $17 \%$ | ...... | 18.. |  | $25 \%$ |  | 26 |  |  |
|  | $1 \%$ |  | 20. |  | $2 \%$ |  | 28 |  |
| 21. | .. | 22. |  | 29. |  | 30 |  |  |
|  | 23. |  | 24... | ...... 3 | 3.1 |  | 32 | 2 |



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