Components Reduction of Double-Layer Networks with Holographic Optical Switches

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Abstract—Combining the unique features of the double-layer network and holographic optical switches not only reduces the volume of the whole system, eliminates all interconnection lines and crossovers significantly, reduces the number of drivers from $N^2/4+2N\log_2 N-2N$ to $2N\log_2 N$, but also the system insertion loss can also be minimized. After rearranging the channels allocation, the number of electro-optic halfwave plates can be significantly decreased from $2N^2-2N$ to $2N\log_2 N$.

Keywords—holographic optical switch, polarization beam splitter, double-layer network, optical interconnection network, electro-optic halfwave plate

1 Introduction

A double-layer network (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 [1-3]. The middle stage has four $(N/2)\times(N/2)$ subnetworks. In the left stage, there are N 1×2 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 2×1 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 number of stages of the 1×2, 2×2, and 2×1 optical switches are k-1, 1, and k-1, respectively, where $k = \log_2 N$. Figure 2 shows a 4×4 double layer network, which the $(N/2)\times(N/2)$ subnetwork is a 2×2 optical switch.

The DLNs 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 SNR compared with any nondilated network [1]. However, they require a large number of switches, interconnection lines, and crossovers. In our previous research, the interconnection lines and crossovers problems can be solved and the system insertion loss can be reduced by using holographic optical switches (HOSs) [2-3]. HOSs are three-dimensional devices [4-9] and the compactness and flexibility of the HOSs are also important characteristics. In this study, the required electro-optic halfwave plates (EOHWPs) [10-11] can be significantly minimized by combining the unique features of the double-layer networks and holographic optical switches.

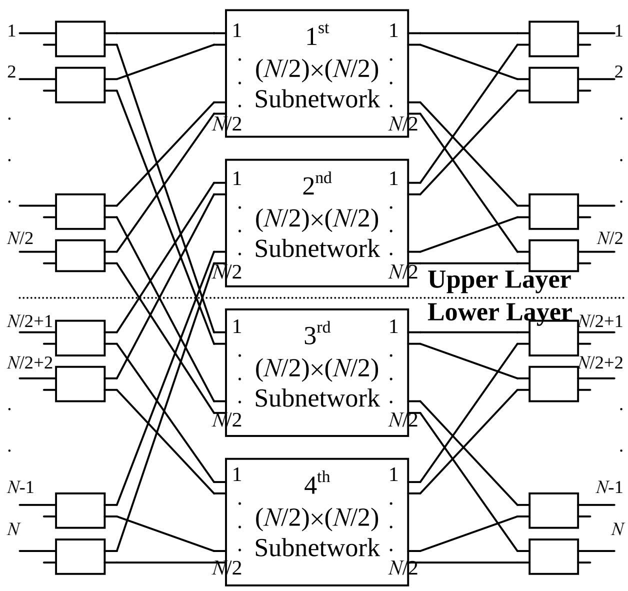

Fig. 1. The basic structure of an $N\times N$ double-layer network.

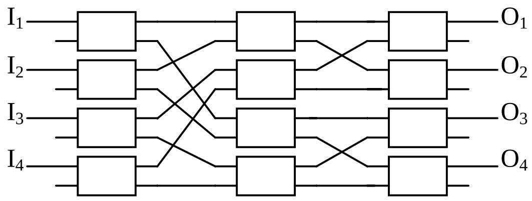

Fig. 2. A 4×4 double-layer network.

2 Holographic Optical Switches

In a double-layer network, the left, innermost, and right stages are 1×2, 2×2, and 2×1optical switches, respectively. These three kinds of HOSs have been designed and proposed [4-9]. Each kind of the basic HOS is composed of a holographic polarization beam splitter (PBS) and two EOHWPs [4-9], and the holographic PBS was sandwiched between these 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.

HOSs perform polarization-dependent characteristics. With suitable designs, highly polarization-selective holographic elements can be achieved, designed, and fabricated [4-9]. The HOSs are three-dimensional devices, and the flexibility and compactness are their advantages. Utilizing these 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 [4, 9, 12-18]. All of HOSs are compact and light-weight, and the feature of normally incident and output coupling provide better flexibility and easier alignment for system applications.

A basic 1×2 HOS consists of an 1×2 holographic PBS and two EOHWPs [2] as shown in Fig. 3. In the 1×2 holographic PBS, two conjugate polarization-selective holographic gratings are formed on two sides of a dielectric substrate. The initial input and final output optical beams are *s*-polarized as shown in these figures. When EOHWPs are inactive, the optical beam keeps *s*-polarization, and passes directly these two EOHWPs and holographic PBS. The 1×2 HOS provides "**straight**" function as shown in Fig. 5(a), where input channel connects to output channel O_1. When EOHWPs are active, the *s*-polarized input optical beam becomes *p*-polarized after passing through the first EOHWP. This optical beam is diffracted by the input coupling holographic grating (HG_I) and coupled normally out with a conjugate diffraction by the output coupling holographic grating (HG_O). The propagation direction of this *p*-polarized optical beam will be turned to 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 1×2 HOS provides "**turn**" function as shown in Fig. 5(b). 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 1×2 HOS provides bi-directional switching function. Therefore, a 1×2 HOS can act as a 2×1 HOS.

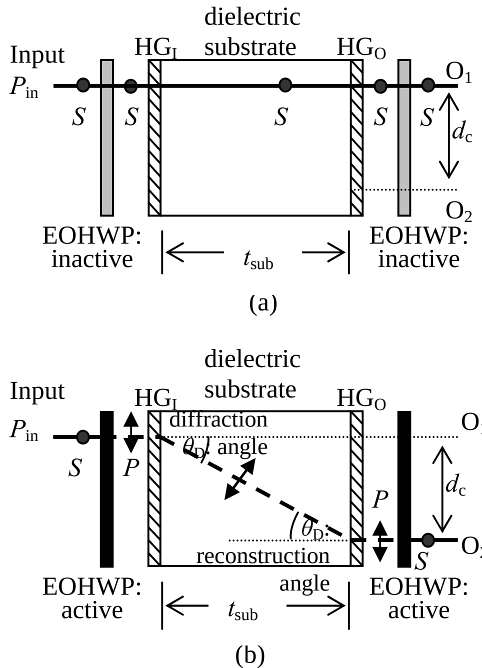

Fig. 3. The switching states of a 1×2 HOS: (a) "**straight**" state and (b) "**turn**" state, where HG and EOHWP are holographic grating and electro-optic halfwave plate. In these two figures, the solid and dash lines are presented the *s*- and *p*-polarized signal paths, respectively.

By the unique features of the DLN, the structure of 1×2 HOS can be modified as shown in Fig. 4, which consists of one 1×2 holographic PBS and one EOHWP [3]. Its insertion loss has been reduced from $L_{PBS}+2L_{EOHWP}$ to $L_{PBS}+L_{EOHWP}$ (dB), where L_{PBS} and L_{EOHWP} are the insertion loss of the holographic PBS and EOHWP, respectively. All of the switching situations are shown in Fig. 4. In Figs. 4(a) and 4(b), the input optical beams are *s*-polarized and the input optical beams are *p*-polarized in Figs. 4(c) and 4(d). Both of Figs. 4(a) and 4(d) provide the "**straight**" state and the output optical beams are *s*-polarized and both of Figs. 4(b) and 4(c) provide the "**turn**" state and the output optical beams are *p*-polarized. 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 1×2 HOS provides bi-directional switching function. Therefore, a 1×2 HOS can act as a 2×1 HOS.

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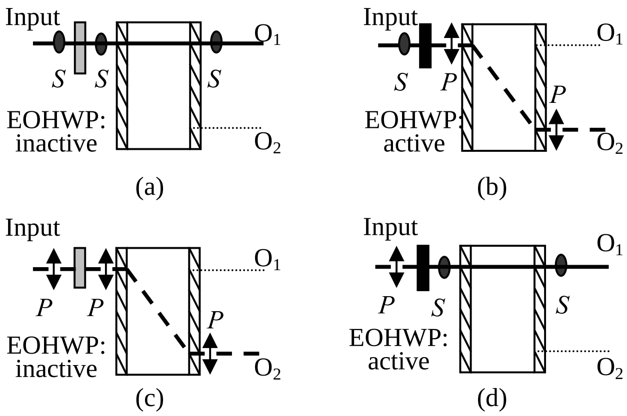

Fig. 4. A simplified 1×2 HOS consists of a holographic PBS and an electro-optic halfwave plate which can provide; (a) "straight" state for *s*-polarized input, (b) "turn" state for *s*-polarized input, (c) "turn" state for *p*-polarized input, and (d) "straight" state for *p*-polarized input, where EOHWP is the electro-optic halfwave plate. In these four figures, the solid and dash lines are presented the *s*- and *p*-polarized signal paths, respectively.

A basic 2×2 HOS consists of two EOHWPs and one 2×2 holographic PBS, in which two symmetric conjugate polarization-selective grating pairs are formed on a dielectric substrate as shown in Fig. 5. Because the structure of this basic 2×2 HOS is symmetric, it provides a bi-directional switching function. When EOHWPs are inactive, the optical beam polarization is not changed. The direction of this optical beam will not be changed by the holographic gratings (HG_I and HG_O). At this time, input channels I_1 and I_2 connect to output channels O_1 and O_2, respectively, and it provides "**straight**" connection as shown in Fig. 5(a). When EOHWPs are active, the optical beam polarization orientation is rotated by 90° and the polarization of this optical beam is *p*-polarized. This optical beam is diffracted by the input coupling holographic grating (HG_I) and normally coupled out with a conjugate diffraction by the output coupling holographic grating (HG_O). Therefore, input channels I_1 and I_2 connect to output channels O_2 and O_1, respectively. In this case, the 2×2 HOS provides "**swap**" connection as shown in Fig. 5(b).

In these holographic HOSs, the distance between two output channels is d_c and the corresponding thickness of the dielectric substrate is t_{sub}. The relation between these two parameters is

$$t_{sub} = d_c \times \cot\theta_D , \qquad (1)$$

where θ_D is the diffraction angle. In other words, when the distances between these two output channels in these HOSs are changed to $2d_c$, the corresponding thickness of the dielectric substrates become $2t_{sub}$.

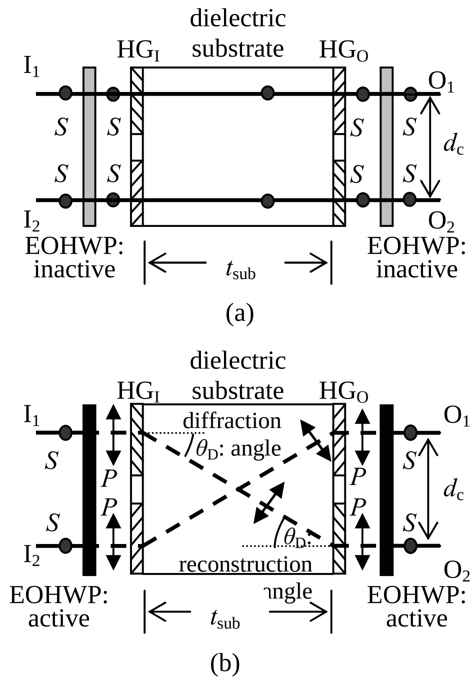

Fig. 5. The switching states of a 2×2 HOS: (a) "**straight**" state and (b) "**swap**" state.

Figure 6 shows the modified 2×2 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 2×2 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×N DLN can be reduced from $N^2/4+2N\log_2 N-2N$ to $2N\log_2 N$.

In an N×N DLN, the numbers of the 1×2, 2×1 and 2×2 HOSs are $N(N/2-1)$, $N(N/2-1)$, and $N^2/4$, respectively, and each connection path has (k-1) 1×2 HOSs, one 2×2 HOS, and (k-1) 2×1 HOSs. Because each 1×2 and 2×1 HOS has been reduced one EOHWP and the number of EOHWPs has been doubled in 2×2 HOSs, the number of the EOHWPs can be reduced from $2.5N^2-4N$ to $2N^2-2N$, and the system insertion loss can be decreased from $(2k-1)(L_{PBS}+2L_{EOHWP})$ to $(2k-2)L_{PBS}+2kL_{EOHWP}$ (dB) [3]. Therefore, the insertion loss and the required components can be reduced by using these three kinds of modified HOSs to construct a DLN.

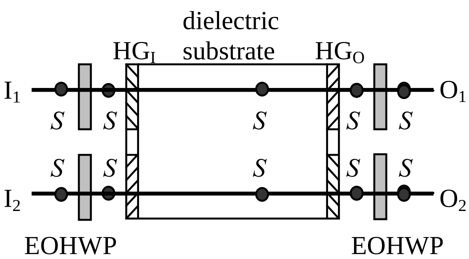

Fig. 6. A 2×2 HOS with four EOHWPs to maintain optical beam polarization.

3 Components Reduction

Figure 7 shows a 4×4 double-layer network with modified HOSs. In the second stage of EOHWPs, the EOHWPs at channels 1 and 5 connect to the same input channel 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×N double-layer network can be reduced from $N^2/4+2N\log_2N-2N$ to $2N\log_2N$ [2].

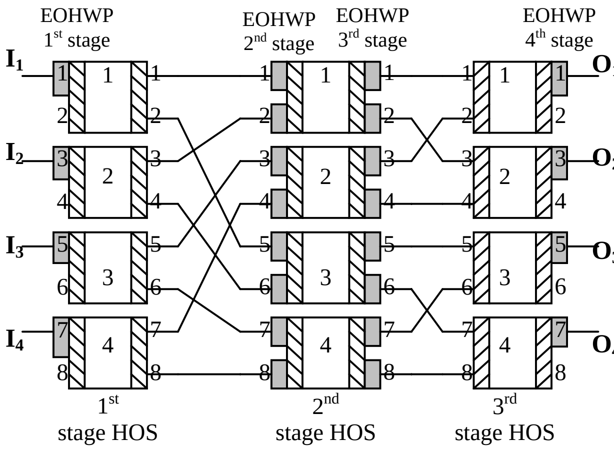

Fig. 7. A 4×4 DLN with modified HOSs.

The channels connection tables of the HOSs and EOHWPs of a 4×4 double-layer network with modified HOSs are shown in Table 1 and Table 2, respectively. Table 2 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 1. 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.

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 3 and Table 4, respectively. In Table 4, 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 4×4 double-layer network, there are four stages of EOHWPS and each stage has four EOHWPs. The total number of EOHWPs is sixteen.

Table 1. The channels connection table of the HOSs in a 4×4 double-layer network, where $2t_{sub}$, t_{sub}, and $2t_{sub}$ are the corresponding thicknesses of the dielectric substrates in the first, second, and third stages of HOSs, respectively.

HOSs 1st stage			
1	5	2	6
3	7	4	8

$2t_{sub}$

HOSs 2nd stage			
1	3	5	7
2	4	6	8

t_{sub}

HOSs 3rd stage			
1	2	5	6
3	4	7	8

$2t_{sub}$

Table 2. The channels connection table of the EOHWPs in a 4×4 double-layer network, where dash circles are the corresponding EOHWPs.

EOHWP 1st stage			
1	5	2	6
3	7	4	8

EOHWP 2nd stage			
1	3	5	7
2	4	6	8

EOHWP 3rd stage			
1	3	5	7
2	4	6	8

EOHWP 4th stage			
1	2	5	6
3	4	7	8

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

HOSs 1st stage			
1		5	
	3		7
2		6	
	4		8

$2t_{sub}$

HOSs 2nd stage			
1		3	
	2		4
5		7	
	6		8

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

HOSs 3rd stage			
1		2	
	3		4
5		6	
	7		8

$2t_{sub}$

Figure 8 shows an 8×8 double-layer network with modified HOSs and its channels connection table of EOHWPs is shown in Table 5. 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 5, 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.

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

EOHWP 1st stage

1		2	
	3		4
5		6	
	7		8

EOHWP 2nd stage

1		5	
	2		6
3		7	
	4		8

EOHWP 3rd stage

1		5	
	2		6
3		7	
	4		8

EOHWP 4th stage

1		5	
	3		7
2		6	
	4		7

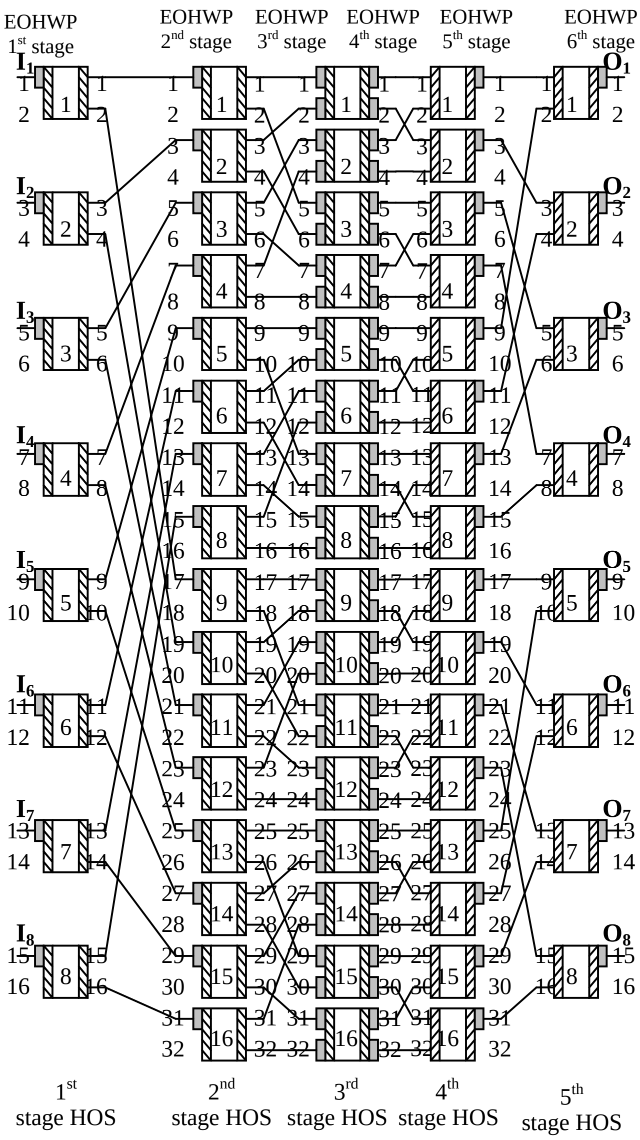

Fig. 8. An 8×8 DLN with modified HOSs.

In figure 8, 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 8×8 double-layer network 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 $2\log_2 N$ stages and its total number of EOHWPs is $2N\log_2 N$ in an $N\times N$ double-layer network with modified HOSs. The number of EOHWPs has been significantly reduced from $2N^2-2N$ to $2N\log_2 N$.

Table 5. The new channels connection table of the EOHWPs in a 8×8 double-layer network, where dash circles are the corresponding EOHWPs.

EOHWPs 1st stage

1		5		9		13	
	3		7		11		15
2		6		10		14	
	4		8		12		16

EOHWPs 2nd stage

1		5		9		13	
	3		7		11		15
2		6		10		14	
	4		8		12		16
17		21		25		29	
	19		23		27		31
18		22		26		30	
	20		24		28		32

EOHWPs 3rd stage

1		3		9		11	
	2		4		10		12
5		7		13		15	
	6		8		14		16
17		19		25		27	
	18		20		26		28
21		23		29		31	
	22		24		30		32

EOHWPs 4th stage

1		3		9		11	
	2		4		10		12
5		7		13		15	
	6		8		14		16
17		19		25		27	
	18		20		26		28
21		23		29		31	
	22		24		30		32

EOHWPs 5th stage

1		2		9		10	
	3		4		11		12
5		6		13		14	
	7		8		15		16
17		18		25		26	
	19		20		27		28
21		22		29		30	
	23		24		31		32

EOHWPs 6th stage

1				2			
	3				4		
5				6			
	7				8		
9				10			
	11				12		
13				14			
	15				16		

4 Conclusions

In our previous researches, combining the unique features of the double-layer network and holographic optical switches not only reduces the volume of the whole system, eliminates all interconnection lines and crossovers significantly, but also reduces the number of drivers from $N^2/4+2N\log_2 N-2N$ to $2N\log_2 N$, the system insertion loss can also be significantly decreased $(2\log_2 N-1)(L_{PBS}+2L_{EOHWP})$ to $(2k-2)L_{PBS}+2kL_{EOHWP})$ (dB), and the number of EOHWPs is reduced from

$5N^2/2$-$4N$ to $2N^2$-$2N$. In this study, the channels allocation have been rearranged when using holographic optical switches to build double-layer and networks. Finally, the number of EOHWPs has been decreased again from $2N^2$-$2N$ to $2N\log_2 N$.

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