Holographic polarization-selective and wavelength-selective elements in optical network applications

Yang-Tung Huang[*], *Der-Chin Su*[**], *Jiun-Shiou Deng*[*], and *Jen-Tsorng Chang*[**]

*: Department of Electronics Engineering and Institute of Electronics
**: Institute of Electro-Optical Engineering
National Chiao Tung University, Hsinchu, Taiwan, Republic of China

ABSTRACT

Volume-type holographic optical elements perform polarization-dependent characteristics, and highly polarization-selective holographic elements can be achieved with suitable designs. In addition, wavelength-selective characteristics can also be designed with volume-type holographic optical elements. These polarization-selective and wavelength-selective components have been designed and fabricated in various structures. In this presentation, we first review the basic structures of our holographic polarization-selective and wavelength-selective elements. Normally incident and output coupling of our compact and light-weight components provide better flexibility and easier alignment for system applications. Based on these holographic optical elements, we will introduce the compact structures for various optical interconnect applications.

Keywords: holographic optical elements, polarization beam splitters, optical networks, wavelength-division-multiplexing, optical interconnection networks.

1. INTRODUCTION

In many optical network systems switching and wavelength-selective elements are required to perform interconnection routing functions.[1–4] Volume-type holographic optical elements perform polarization-dependent characteristics.[5] With suitable designs, highly polarization-selective holographic elements can be achieved, and these components have been designed and fabricated.[6–12] In this presentation, we first review the basic structure of our holographic polarization-selective elements. Based on our holographic polarization-selective elements with electro-optic halfwave plates, we also introduce holographic polarization-dependent and polarization-independent optical switches. In addition, wavelength-selective characteristics can also be designed with volume-type holographic optical elements, and these elements have been designed and fabricated in various structures.[13–16]

In a wavelength-division multiaccess (WDMA) network passive star couplers are important elements. The function of a star coupler is to distribute optical power of each input beam associated with a unique wavelength equally to all outputs with their respective tunable receivers.[17,18] With suitable arrangements, our holographic polarization-selective elements can be used to implement polarization-dependent and polarization-independent star couplers. With holographic optical switches to implement various three-dimensional multistage interconnection networks for reconfigurable interconnections are also discussed.[19–20] In addition, the basic structures of our wavelength-selective elements in optical network applications are introduced.[13–16] All of our devices are compact and light-weight, and the feature of normally incident and output coupling provide better flexibility and easier alignment for system applications.

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2. HOLOGRAPHIC POLARIZATION-SELECTIVE ELEMENTS

The basic structure of our holographic polarization-selective elements is shown in Fig. 1.[6-12] Two symmetric polarization-selective grating pairs are formed on two sides of a dielectric substrate. The diffraction angle in the film medium is θ_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 output coupling, the reconstruction angle is θ_D and the output diffracted beam is also normal to the device as shown in Fig. 1. Based on Kogelnik's coupled wave theory,[5] the diffraction efficiencies of s- and p-polarization fields with respect to the grating plane for each grating, η_s and η_p, are respectively given as

$$\eta_s = \sin^2 \frac{\pi n_1 d}{\lambda \sqrt{\cos\theta_D}}, \qquad \eta_p = \sin^2 \frac{\pi n_1 d \sqrt{\cos\theta_D}}{\lambda}, \tag{1}$$

where λ is the operating wavelength, d is the thickness of the grating film, and n_1 is the index modulation of the grating, respectively. From the above equations, suitable values for θ_D and $n_1 d/\lambda$ can be solved as shown in Table 1 to obtain 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), and these devices have been designed and some were fabricated.[6-12]

Using s-transmission/p-diffraction gratings in the structure shown in Fig. 1 as an example, when the input beams are s-polarized, the device will perform the function of **straight** connections (direct transmission) as shown by the solid connection lines in the figure. On the other hand, when the input beams are p-polarized, the device will perform the function of **swap** connections (diffraction) as shown by the dashed connection lines. (For s-diffraction/p-transmission gratings, this holographic polarization-selective element will perform s-**swap**/p-**straight** function.)

3. STAR COUPLERS USING HOLOGRAPHIC POLARIZATION-SELECTIVE ELEMENTS

3.1 Polarization-dependent star couplers

A basic 2×2 coupler with our holographic polarization-selective elements to construct our polarization-dependent passive star coupler is operated as shown in Fig. 2. When the polarization of light from the laser source is specified, the polarization of input light is arranged such that it has the same amount of s- and p-components with respect to the grating planes, i.e., 45° with respect to the x- and y-axes as shown in the figure. Two input signals from channels 1 and 2 with wavelengths of λ_1 and λ_2, respectively, are normally incident on the device. Since the device performs s-**straight**/p-**swap** connection, s-and p-components of signals with wavelength λ_1 from channel 1 will be equally distributed to channels $1'$ and $2'$, respectively. On the other hand, p- and s-components of signals with wavelength λ_2 from channel 2 will be equally distributed to channels $1'$ and $2'$, respectively. This 2×2 coupler is the basic unit to form our holographic star couplers.

In order to implement a star coupler, an efficient $N \times N$ connection network is also required. A 16×16 shuffle interconnection network for our one design example is shown in Fig. 3.[20] Based on the shuffle network structure and channel number assignment illustrated in Fig. 3, we can obtain a table to describe channel connection relations between stages as shown in Table 2. From these connection relations, we determine mapping tables of all stages as shown in Fig. 4(a). The numbers of these mapping tables indicate the corresponding input channel numbers of all stages. For example, the output of channel 1 at stage 1 is connected to the input of channel 1 at stage 2, whereas the output of channel 2 at stage 1 is connected to the input of channel 3 at stage 2. In these mapping tables each channel pair to form a coupler is at 45° with respect to the corresponding pair of the preceding stage. In this case, the polarization of the output optical field of each channel is at 45° with respect to the input grating plane of the following stage, and the optical power can be equally distributed to two output channel through the coupler as shown in Fig. 4(b) and (c).

Fig. 4(b) shows the grating pairs for all couplers at all stages. Each two-end arrow represents a grating pair of a coupler corresponding to the channel numbers in Fig. 3. Each quantity in the tables represents the output power ratio compared to the input power of the first stage. In this power distribution description example, we only couple an optical power into the input of channel 1 at the first stage. The corresponding polarizations of input and output optical fields of all stages are shown in Fig. 4(c). In this figure, x'- and y' axes are at 45° with respect to x- and y-axes. When an optical field with a unity power and the polarization at x'-direction is incident to channel 1 of the first stage, then the power of $1/2$ is distributed to output channel 1 with the polarization at x-direction and $1/2$ to channel 2 at y-direction, and goes to input channels 1 and 3 of the second stage. Through the couplers at the second stage, the power of $1/4$ is distributed to channels $1, 2, 3, 4$, and the corresponding input channel numbers of the third stage are $1, 3, 5, 7$. Through the third stage, the power of $1/8$ is distributed to channel $1, 2, \ldots, 7, 8$, and the corresponding input channel numbers of the fourth stage are $1, 3, \ldots, 13, 15$. Finally, through the fourth stage, the power of $1/16$ to each channel is equally distributed to channels 1–16 as shown in the figure, and the function of a star coupler is achieved. Optical fields with the polarization at x'-direction incident to other channels will follow the same process to equally distribute the power to all channels through the whole star coupler. As shown in Fig. 2, the required thickness of a coupler is proportional to the distance between the centers of two coupled channel, and the corresponding thicknesses t, $\sqrt{2}t$, $2t$, and $2\sqrt{2}t$ for all stage layers are also shown in Fig. 4(b). When grating pairs are fabricated with the corresponding substrate thickness as shown in 4(b), all suitable coupler layers are formed. Stacking all layers in order as shown in the figure, a compact holographic star coupler with no interconnection lines is built. To view the three-dimensional structure of this device for easy understanding, the three-dimensional configuration for a 4×4 star coupler composed of two stages of holographic polarization-selective elements is illustrated in Fig. 5.

The procedures to design a passive star coupler using our holographic polarization-selective elements can be summarized as:

(1) Determine an efficient connection network, such as a shuffle network in our case shown in Fig. 3, based on 2×2 coupler, where i-th (odd number) and $(i+1)$-th channels form a pair of 2×2 coupler at each stage to equally distribute optical power from one input channel into two output channels as shown in Fig. 2.

(2) Determine the channel connection tables from the network connection structure as shown in Table 2.

(3) Assign input channel numbers of hologram set for each stage to form mapping tables as shown in Fig. 4(a). Each pair must be maintained at 45° with respect to the pair of the same designated channel numbers of the preceding stage such that optical power at the input of each channel can be equally distributed into two channels with two different (s- and p-) polarizations through one 2×2 holographic coupler as shown in Fig. 2.

(4) Determine the orientation of each grating plane pair based on the rule that i-th (odd number) and $(i+1)$-th channels form a pair at each stage, and determine the corresponding thickness of the polarization beamsplitter set for each stage, which is proportional to the center distance of the grating pair as shown in Fig. 4(b).

(5) Follow the mapping tables to stack all stages in order, a compact holographic star coupler with no connection lines between stages is constructed.

3.2 Polarization-independent star couplers

In some applications such as fiber optic communications, the input light of a star coupler might not be linearly polarized. In this case, the above polarization-dependent star coupler is not suitable. Therefore, we need to design polarization-independent star couplers for this kind of applications.

The proposed method is to add one more stage in front of the first stage of the original polarization-dependent star coupler and with a grating structure the same as the original second stage (45° with respect to the original first stage) such that the input beams can be splitted to two orthogonal polarized fields and both these two orthogonal polarized fields can be equally distributed to all output channels through the original polarization-dependent star coupler. Therefore, all output channels obtain equal optical power for both two orthogonal polarized fields. Fig. 6 shows the polarization of the fields and the power distribution process is illustrated. As shown in the figure, x and y are the unknown proportions for two orthogonal polarizations of an input beam, and splitted to two directed channels after passing the first stage. For a $N \times N$ star coupler with $log_2 N + 1$ stages, the output power for each channel is about $(x + y)/N$ (for a low-loss case). The power distribution process for a 16×16 star coupler is illustrated in Fig. 6.

4. HOLOGRAPHIC OPTICAL SWITCHES FOR INTERCONNECTION NETWORKS

4.1 Polarization-dependent optical switches

2×2 switch is a basic unit for multistage switching networks[19–20]. Basically, a polarization beam splitter (PBS) in conjunction with an electro-optic halfwave can form this type of optical switch. Wollaston and Rochen prism cubes are conventionally used for polarization beamsplitting. Our holographic polarization-selective elements can be used to replace conventional prism cube PBSs in switching applications.[6–11] The typical unidirectional polarization-dependent holographic optical switch with our structure is shown in Fig. 1. These type switches are used only for specified linearly-polarized input beams (s- or p-polarization with respect to the grating planes). In the example shown in the figure, the input beams are s-polarized. When the electro-optic half plate is inactive (state 0), the switch performs the **straight** connections (solid lines); when the plate is active (state 1), the fields are rotated by 90° and the device performs the **swap** connections (dashed lines).

4.2 Polarization-independent holographic optical switches

Polarization-independent optical switches with electro-optic halfwave plates and polarization beamsplitting prisms have also been investigated.[21] The structure we propose for a polarization-independent holographic optical switch is shown in Fig. 7(b). This switch is composed of an electro-optic halfwave plate sandwiched by two holographic polarization-selective elements. In this example the gratings perform s-transmission/p-diffraction functions. For convenience of discussion, we denote six positions on the connection paths by points A_1, A_2 (corresponding to channels 1 and 2), P_1, P_2 (corresponding to plate positions), and A'_1, A'_2 (corresponding to channels $1'$ and $2'$). The inactive state (State 0) of the electro-optic halfwave plate will make the switch perform the function of bidirectional **straight** connections ($1 \leftrightarrow 1'$, $2 \leftrightarrow 2'$) as shown in Fig. 7(b). In the other case, i.e., when the electro-optic halfwave plate is active (State 1), the field polarizations will be changed after passing through the plate, and the electro-optic halfwave plate will make the switch perform the function of bidirectional **swap** connections ($1 \leftrightarrow 2'$, $2 \leftrightarrow 1'$). All connection states are also clearly shown in Table 3.

Various multistage interconnection networks can be implemented by holographic optical switches described above with very threeidimensional compact forms.

5. HOLOGRAPHIC WAVELENGTH-SELECTIVE ELEMENTS IN NETWORK APPLICATIONS

Some architectures considered for WDM (wavelength-division-multiplexing) networks require wavelength routing elements[1-2] and several basic elements for wavelength routing purpose have been demonstrated [22-23]. Since volume-type holographic elements perform wavelength-dependent characteristics, we have investigated holographic wavelength-selective elements for wavelength routing function in network applications.

The basic wavelength routing structure with four different wavelengths ($\lambda_1, \lambda_2, \lambda_3$, and λ_4) is shown in Fig. 8. There are four input and four output holographic elements corresponding to Channel 1, 2, 3, and 4. Each holographic element consists of three gratings, and each grating diffract only one specific wavelength beam. In our structure for λ_1 beams, the elements perform no diffraction and i-th input channel will directly connect to i-th input channel as shown in Fig. 8(a). On the other hand, for λ_2 beams the elements perform diffractions as shown in Fig. 8(b) and i-th input channel will connect to $i+1$-th input channel; for λ_3 beams the elements perform diffractions as shown in Fig. 8(a) and i-th input channel will connect to $i+2$-th input channel; for λ_4 beams the elements perform diffractions as shown in Fig. 8(b) and i-th input channel will connect to $i+3$-th input channel.

In our design, we use 670, 830, 1300, and 1550 nm as our four working wavelengths. For these four operating wavelengths the wavelength separation are large enough (> 100 nm) to have negligible crosstalks. Our experimental results show the possibility to apply these holographic wavelength-selective elements in network cross-connect applications.[12]

6. SUMMARY

In this presentation, the basic structure of our holographic polarization-selective elements are reviewed. With suitable designs and arrangements, these elements can be combined to implement polarization-dependent and polarization-independent star couplers to distribute equal optical power from each input channel to all output channels. Based on our holographic polarization-selective elements with electro-optic halfwave plates, holographic polarization-dependent and polarization-independent optical switches are discussed. The structures to use these switches in various compact three-dimensional multistage interconnection networks for reconfigurable interconnections are presented. Holographic wavelength selective elements for cross-connect in network applications are introduced. All of our devices are compact and light-weight, and the feature of normally incident and output coupling provide better flexibility and easier alignment for system applications.

7. ACKNOWLEDGEMENT

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References

1. M. Karehrad and M. Tabiani, "A selective-broadcast passive star couple for self-routing dense wavelength division-multiplexed optical networks," *IEEE J. Lightwave Technol.*, vol. LT-9, pp. 1278–1288, 1991.

2. M. I. Irshid, and M. Kavehrad, "A WDM cross-connected star topology for multihop lightwave networks," *IEEE J. of Lightwave Technol.*, vol. 10, no. 6, pp. 828–835, June 1992.

3. K. M. Sivalingam, and P. W. Dowd, "A multilevel WDM access protocol for an optically interconnected multiprocessor system," *IEEE of Lightwave Technol.*, vol. 13, no. 11, pp. 2152–2167, Nov. 1995.

4. J. Helms, A. Reichelt, M. Semjen, and B. H. Verbeek, "32 digital uncompressed tv channel distribution via 8 HDWDM channels," *IEEE of Lightwave Technol.*, vol. 13, no. 8, pp. 1648–1654, Aug. 1995.

5. H. Kogelnik, "Coupled wave theory for thick hologram gratings," *Bell Sys. Tech. J.*, vol. 48, no. 9, pp. 2909–2947, Nov. 1969.

6. M. Kato, H. Ito, T. Yamamoto, F. Yamagishi, and T. Nakagami, "Multichannel optical switch that uses holograms," *Opt. Lett.*, vol. 17, no. 11, pp. 769–771, June 1992.

7. Y.-T. Huang and Y.-H. Chen, "Polarization-selective elements with a substrate-mode grating pair structure," *Opt. Lett.*, vol. 18, no. 11, pp. 921–923, June 1993.

8. Y.-T. Huang, "Polarization-selective volume holograms: general design," *Appl. Opt.*, vol. 33, no. 10, pp. 2115–2120, April 1994.

9. Y.-T. Huang and Y.-H. Chen, "Optical switches with a substrate-mode grating structure," *Optik*, vol. 98, no. 1, pp. 41–44, Nov. 1994.

10. J.-T. Chang, D.-C. Su, and Y.-T. Huang, "Substrate-mode holographic polarization-division multi/demultiplexer for optical communications," *Appl. Opt.*, vol. 33, no. 35, pp. 8143–8145, Dec. 1994.

11. Y.-T. Huang "Polarization-independent optical switch composed of holographic optical elements," *Opt. Lett.*, vol. 20, no. 10, May 15, 1995.

12. J.-T. Chang, D.-C. Su, and Y.-T. Huang, "A four channel polarization and wavelength separation element using substrate-mode stacked holograms," *Appl. Physics Lett.*, vol. 68, no. 25, pp. 3537–3539, 1996.

13. Y.-T. Huang, D.-C. Su, and Y.-K. Tsai, "Wavelength-division-multiplexing and demultiplexing using a substrate-mode grating pair," *Optics Letters*, vol. 17, no.22, pp. 1629-1631, Nov. 1992.

14. Y.-K. Tsai, Y.-T. Huang, and D.-C. Su, "A reflection-type substrate-mode grating structure for wavelength-division-multi/demultiplexing ," *Optik*, vol. 97, no. 2, pp. 62–66, Oct. 1993.

15. Y.-K. Tsai, Y.-T. Huang, and D.-C. Su, "Multi-band wavelength-division-demultiplexing with a cascaded substrate-mode grating structure," *Applied Optics*, vol. 34, no. 25, pp. 5582–5588, Sept. 1995.

16. J.-T. Chang, D.-C. Su and Y.-T. Huang, "A wavelength and polarization selector made of holographic polarization beamsplitting," *Applied Physics Letters.* vol. 70, no. 14, April 1997.

17. I. P. Kaminow, P. P. Lannone, J. Stone, and L. W. Stulz, "FDM-FSK star network with a tunable optical filter demultiplexer" , *Electronics Lett.,* vol. 23, pp. 1102-1103, 1987.

18. H. S. Hinton, "Photonics in switching," *IEEE LTS*, pp. 26-35, Aug. 1992.

19. A. Lohmann, "Optical bus network," *Optik*, vol. 74, no. 1, pp. 30–35, Jan. 1986.

20. C.-T. Lea, "Multi-$\log_2 N$ networks and their applications in high-speed electronic and photonic switching systems," *IEEE Trans. on Commmun.*, vol 38, no. 10, pp. 1740-1749, Oct. 1990.

21. Y. Fujii, "Low-crosstalk 2 × 2 optical switch composed of twisted nematic liquid crystal cells," *IEEE Photon. Technol. Lett.*, vol. 5, no. 6, pp. 715–718, June 1993.

22. B. Cantanzaro, J. Ma, Y. Fainman, and S. H. Lee, "Wavelength-multiplexed re-configurable interconnect using a volume holographic lens array," *Opt. Lett.*, vol. 19, no. 7, pp. 1358–1360, Sep.1994.

23. A. G. Deryagin, D. V. Kuksenkov, V. I. Kuchinskii, E. L. Portnoi, and V. B. Smirnitskii, "Wavelength and polarization switching in InGaAsP/InP DFB lasers," *IEE Proc.-Optoelectron,*, vol. 142, no. 1, pp. 51–54, Feb. 1995.

TABLE 1: PARAMETER VALUES OF POLARIZATION-SELECTIVE GRATINGS

ν_s	π	$\frac{3}{2}\pi$	2π
ν_p	$\frac{1}{2}\pi$	π	$\frac{3}{2}\pi$
η_s	0%	100%	0%
η_p	100%	0%	100%
θ_D	60.0°	48.2°	41.4°
$n_1 d/\lambda$	.707	1.22	1.73

TABLE 2: CHANNEL CONNECTIONS BETWEEN STAGES OF A SHUFFLE NETWORK

Out channel of i-th stage → Input channel of $(i+1)$-th stage

4×4	8×8	16×16
$1 \to 1+2\times 0 = 1$	$1 \to 1+2\times 0 = 1$	$1 \to 1+2\times 0 = 1$
$2 \to 1+2\times 1 = 3$	$2 \to 1+2\times 1 = 3$	$2 \to 1+2\times 1 = 3$
$3 \to 2+2\times 0 = 2$	$3 \to 1+2\times 2 = 5$	$3 \to 1+2\times 2 = 5$
$4 \to 2+2\times 1 = 4$	$4 \to 1+2\times 3 = 7$	$4 \to 1+2\times 3 = 7$
	$5 \to 2+2\times 0 = 2$	$5 \to 1+2\times 4 = 9$
	$6 \to 2+2\times 1 = 4$	$6 \to 1+2\times 5 = 11$
	$7 \to 2+2\times 2 = 6$	$7 \to 1+2\times 6 = 13$
	$8 \to 2+2\times 3 = 8$	$8 \to 1+2\times 7 = 15$
		$9 \to 2+2\times 0 = 2$
		$10 \to 2+2\times 1 = 4$
		$11 \to 2+2\times 2 = 6$
		$12 \to 2+2\times 3 = 8$
		$13 \to 2+2\times 4 = 10$
		$14 \to 2+2\times 5 = 12$
		$15 \to 2+2\times 6 = 14$
		$16 \to 2+2\times 7 = 16$

TABLE 3: CONNECTION STATES OF POLARIZATION-INDEPENDENT HOLOGRAPHIC OPTICAL SWITCH WITH s-TRANSMISSION/p-DIFFRACTION

	Plate state	Field polarization on the signal path	Connection state	Switch function
GRATINGS	0 (inactive)	$A_1 \overset{s}{\longleftrightarrow} P_1 \overset{s}{\longleftrightarrow} A'_1$ $A_1 \overset{p}{\longleftrightarrow} P_2 \overset{p}{\longleftrightarrow} A'_1$	$1 \longleftrightarrow 1'$	**Straight** connections
		$A_2 \overset{s}{\longleftrightarrow} P_2 \overset{s}{\longleftrightarrow} A'_2$ $A_2 \overset{p}{\longleftrightarrow} P_1 \overset{p}{\longleftrightarrow} A'_2$	$2 \longleftrightarrow 2'$	
	1 (active)	$A_1 \overset{s}{\longleftrightarrow} P_1 \overset{p}{\longleftrightarrow} A'_2$ $A_1 \overset{p}{\longleftrightarrow} P_2 \overset{s}{\longleftrightarrow} A'_2$	$1 \longleftrightarrow 2'$	**Swap** connections
		$A_2 \overset{s}{\longleftrightarrow} P_2 \overset{p}{\longleftrightarrow} A'_1$ $A_2 \overset{p}{\longleftrightarrow} P_1 \overset{s}{\longleftrightarrow} A'_1$	$2 \longleftrightarrow 1'$	

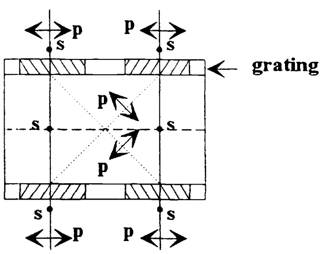


Fig. 1 The structure of a holographic polarization-selective element.

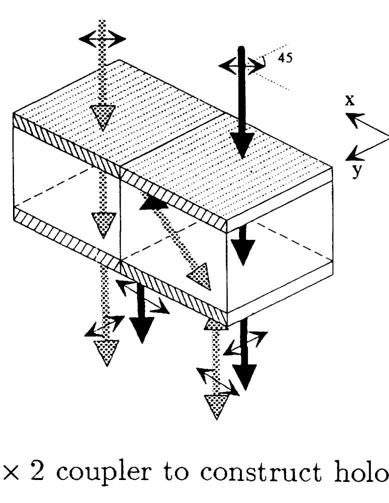


Fig. 2 The structure of a 2×2 coupler to construct holographic star couplers.

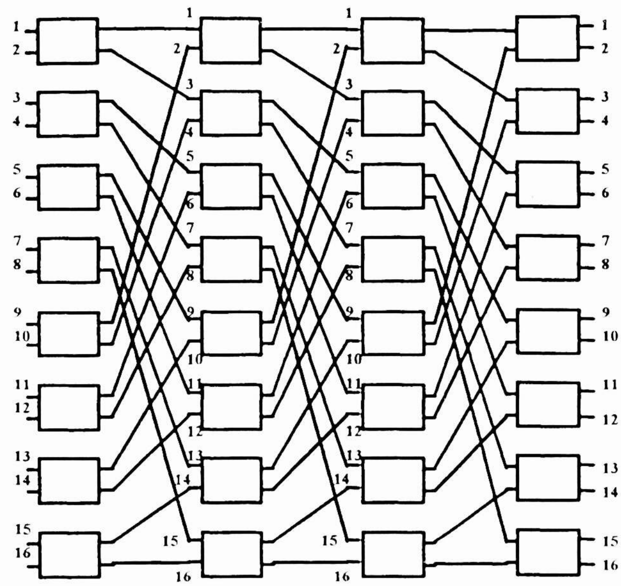


Fig. 3 16 × 16 Shuffle network.

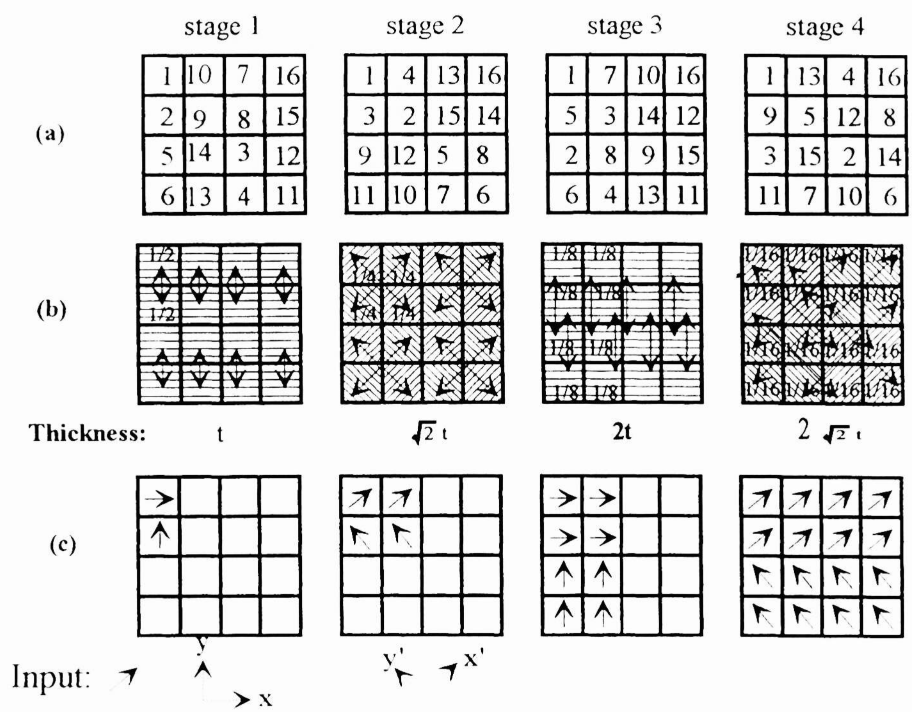
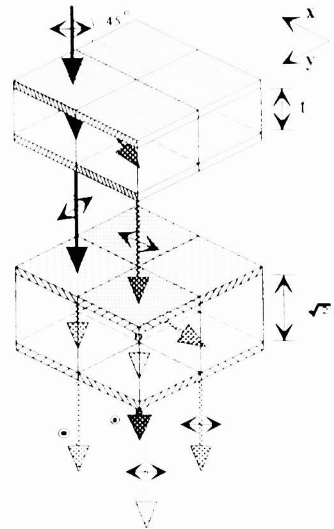


Fig. 4 Power distribution process of a 16 × 16 star coupler. (a) Mapping tables. (b) Grating orientations, device thicknesses, and power distribution ratio. (c) Output field polarizations at each channel.

Fig. 5 Three-dimensional structure of a 4 × 4 polarization-dependent star coupler.



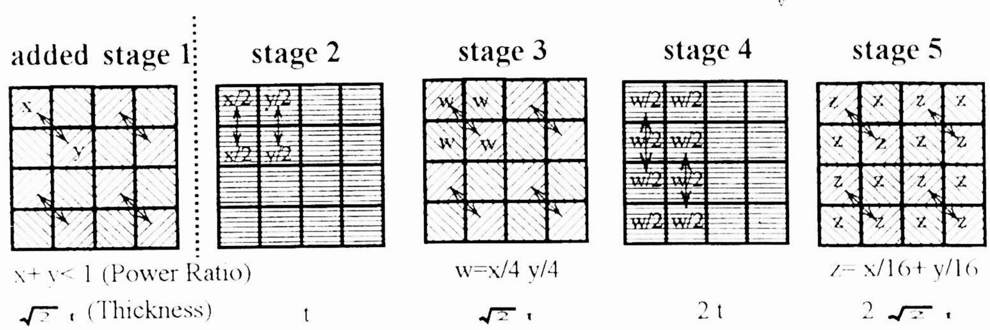


Fig. 6 Grating orientations, device thicknesses and power distribution ratio at each stage of a 16 × 16 polarization-independent star coupler.

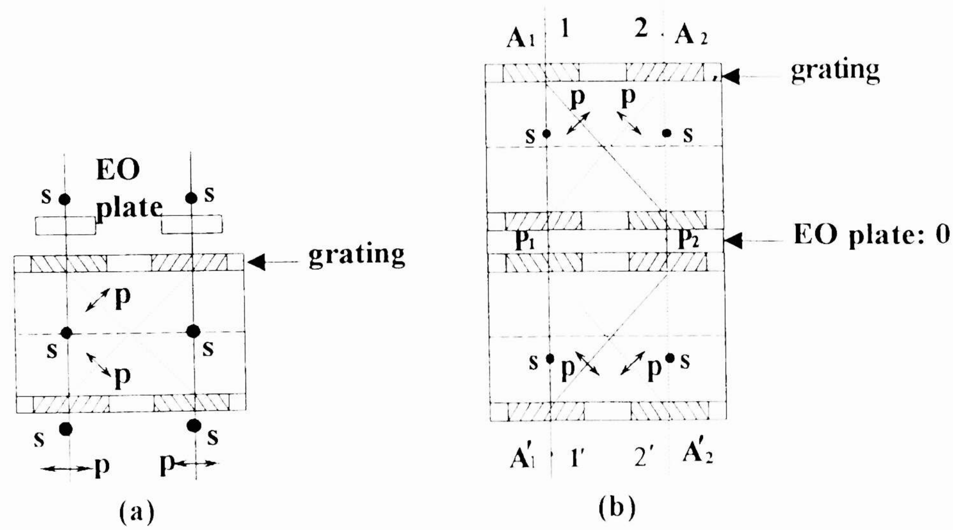


Fig. 7 The structure of a holographic optical switch s-transmission /p-diffraction gratings. (a) Unidirectional polarization-dependent switch. (b) Bidirectional polarization-independent switch.

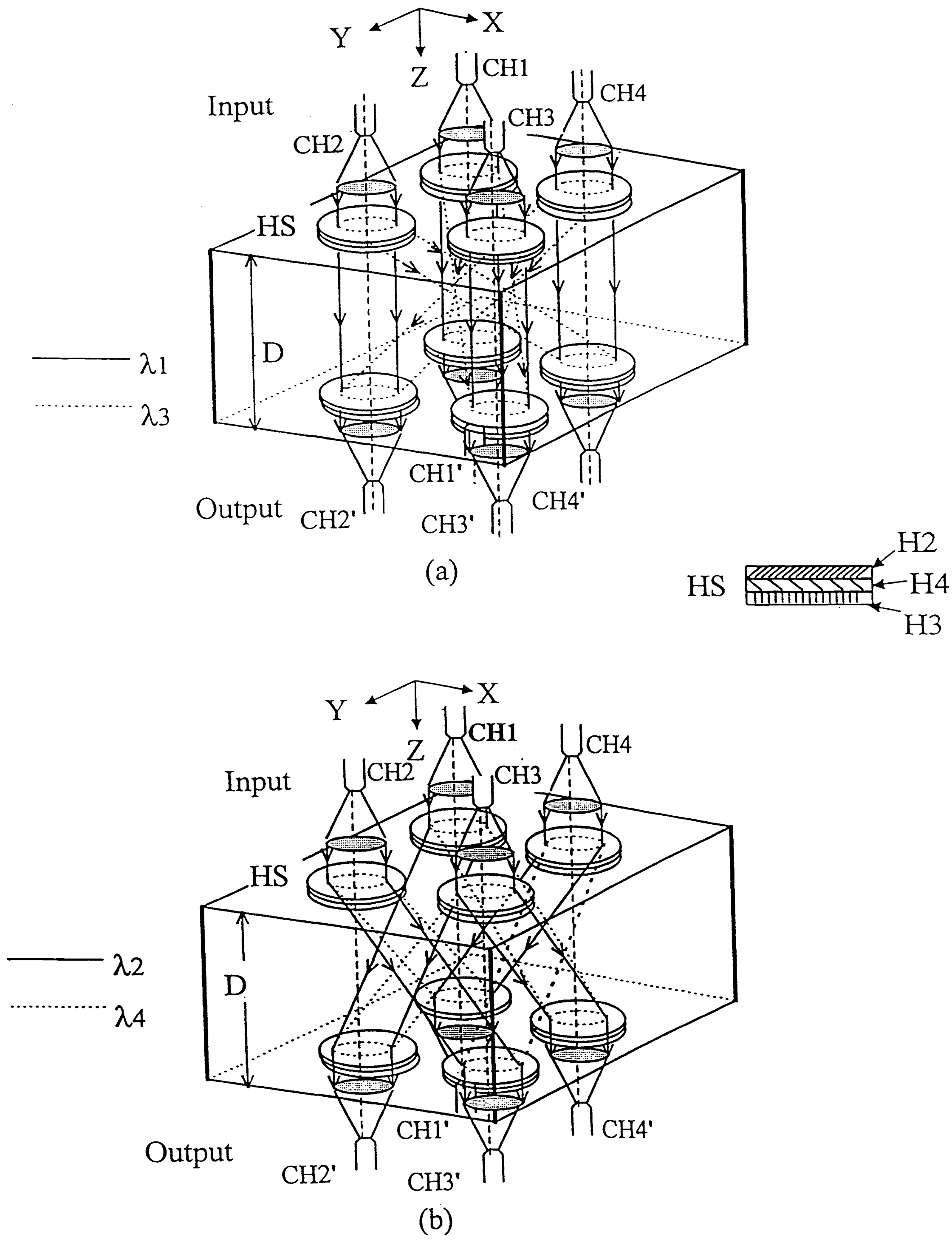


Fig. 8 Routing paths for a holographic wavelength-selective element. (a) λ_1, λ_3. (b) λ_2, λ_4.