# A High Contrast Ratio Optical Switch with Holographic Optical Switching Elements

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*Abstract:* A 2×2 high contrast ratio optical switch composed of holographic optical switching elements is presented. This switch consists of two electro-optic halfwave plates, four layers of holographic gratings, two dielectric substrates, and one spacer. The contrast ratio can be higher than 54 dB. The contrast ratio improvement of this device is the same as a dilated optical switch.

*Key-words:* Holographic optical switching element, Optical switch, Optical interconnection network, Photonic switching, Contrast ratio, Crosstalk, Signal-to-noise ratio, Polarization beam splitter.

## 1 Introduction

There are two kinds of technologies to improve the signal-to-noise ratio (SNR) of optical interconnection networks. The first is to modify the network structure, such as dilated Benes network, modified dilated Benes network, and generally modified dilated Benes network [1, 2]. The second is to dilate the optical switch, such as dilated double-layer network and modified Benes network [3, 4]. These technologies all need a large amount of optical switches.

Holographic optical switching elements (HOSEs) have polarization-dependent characteristics. By well designs, highly polarization-selective holographic elements can be designed and fabricated [5-11]. The HOSEs are three-dimensional devices, and have the advantages of flexibility and compactness. Utilizing these features, the sizes of the HOSEs can be adjusted, which may eliminate the necessity of interconnection lines between optical switches [11-15]. Compared with integrated electro-optic devices on Ti:$LiNbO_3$ material [16] or prism polarization beam splitters (PBSs) in conjunction with electro-optic halfwave plates [17], HOSEs are more suitable to build optical interconnection networks.

In this paper, a high contrast ratio optical switch with HOSEs is proposed. This optical switch is used to replace the dilated optical switch. Therefore, a higher SNR optical interconnection network with fewer optical switches is becoming possible.

## 2 Signal-to-Noise Ratio Analyses of Optical Switches

The crosstalk is the noise for the desired optical signal. When two optical signals pass through a 2×2 optical switch, each desired optical signal in the output has a little crosstalk from the other signal as shown in Fig. 1(a). In this figure, points A, C and D are the input channel, the desired output channel, and undesired output channel, respectively. When the input optical power is $P_{in}$, the optical power at desired output channel (C) and undesired output channel (D) are $(1-\varepsilon)P_{in}$ and $\varepsilon P_{in}$, respectively, where $\varepsilon$ is the crosstalk in a single 2×2 optical switch. The contrast ratio is the optical power ratio between the desired and undesired output channels. In this 2×2 optical switch, the contrast ratio (CR) can be calculated as

$$\mathrm{CR} = \frac{(1-\varepsilon)p_{in}}{\varepsilon p_{in}} \cong \frac{1}{\varepsilon}. \quad (1)$$

The relation between contrast ratio and SNR is shown below:

$$\mathrm{SNR} = 10\log_{10}(\mathrm{CR}) = 10\log_{10}\left[\frac{1}{\varepsilon}\right] = |X| \quad \text{(dB)}, \quad (2)$$

where $X$ is the crosstalk of a single 2×2 optical switch in dB. The typical value of the $X$ is -20 dB ($\varepsilon$ = 0.01).

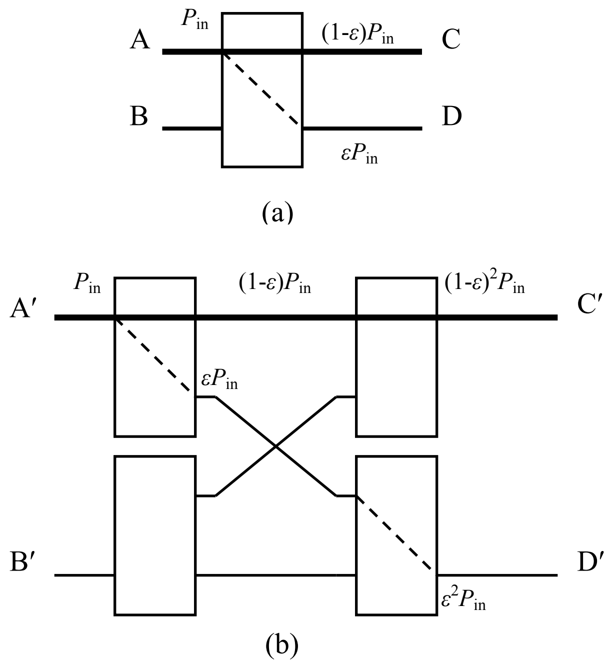


Fig. 1 The crosstalk in an optical switch: (a) single optical switch; (b) dilated optical switch.

Fig. 1(b) shows a 2×2 dilated optical switch, points A′, C′ and D′ are the input channel, the desired output channel, and undesired output channel, respectively. When the input optical power is $P_{in}$, the optical power at desired output channel (C′) and undesired output channel (D′) are $(1-\varepsilon)^2 P_{in}$ and $\varepsilon^2 P_{in}$, respectively. In this dilated 2×2 optical switch, the contrast ratio (CR′) can be calculated as

$$\mathrm{CR}' = \frac{(1-\varepsilon)^2 p_{in}}{\varepsilon^2 p_{in}} \cong \frac{1}{\varepsilon^2}. \qquad (3)$$

The relation between contrast ratio (CR′) and SNR in this dilated 2×2 optical switch is shown below:

$$\mathrm{SNR} = 10\log_{10}(\mathrm{CR}') = 10\log_{10}\left[\frac{1}{\varepsilon^2}\right] = 2|X| \ \ (\mathrm{dB}). \qquad (4)$$

In this 2×2 dilated optical switch, the contrast ratio increases from $1/\varepsilon$ to $1/\varepsilon^2$, which results in the higher SNR. The SNR has been raised from $|X|$ to $2|X|$ (dB). Notice that the 2×2 dilated optical switch needs four 2×2 optical switches.

## 3 Holographic Optical Switching Element

In a 1×2 holographic PBS shown in Fig. 2, two conjugate polarization-selective holographic grating pairs are formed on two sides of a dielectric substrate. The diffraction angle in the dielectric substrate is $\theta_D$, and the Bragg reconstruction input angle is 0°, i.e. the input optical beam is normally incident on the device. The reconstruction angle is $\theta_D$ in the output coupling and the output diffracted optical beam is also normal to the device as shown in Fig. 2(b). Based on Kogelnik's coupled wave theory for a volume type of grating [18], the diffraction efficiencies of *s*- and *p*-polarization fields with respect to the grating plane, $\eta_s$ and $\eta_p$, are given as

$$\eta_s = \sin^2 v_s, \qquad (5)$$

$$\eta_p = \sin^2 v_p, \qquad (6)$$

where the modulation parameters, $v_s$ (*s*-polarization) and $v_p$ (*p*-polarization), are

$$v_s = \frac{\pi n_g d_g}{\lambda\sqrt{\cos\theta_D}}, \qquad (7)$$

$$v_p = v_s \cos\theta_D = \frac{\pi n_g d_g \sqrt{\cos\theta_D}}{\lambda}, \qquad (8)$$

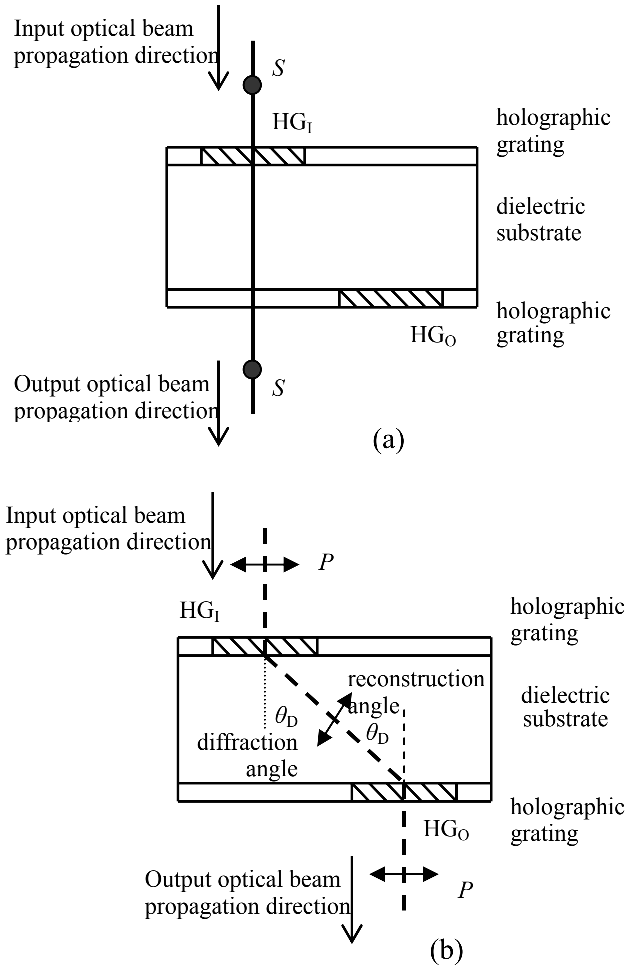


Fig. 2 A 1×2 holographic PBS, where $HG_I$ and $HG_O$ are the input and output holographic gratings, respectively. In this device, the propagation directions of input and output channels are the same.

respectively. In above equations, $\lambda$ is the operating wavelength, $d_g$ is the thickness of the grating film, and $n_g$ is the index modulation of the grating. Values of $\theta_D$ and $n_g d_g/\lambda$ solved from Eqs. (7) and (8) are shown in Table 1. These high polarization-selectivity (0%- and 100%- diffraction for *s*- and *p*-polarization fields, respectively) devices have been designed and some were fabricated [5-11].

Table 1 Parameters of polarization-selective grating.

| $v_s$ | π | 3π/2 | 2π |
|---|---|---|---|
| $v_p$ | π/2 | π | 3π/2 |
| $\eta_s$ | 0% | 100% | 0% |
| $\eta_p$ | 100% | 0% | 100% |
| $\theta_D$ $\cos^{-1}(v_p/v_s)$ | 60.0° $\cos^{-1}(1/2)$ | 48.2° $\cos^{-1}(2/3)$ | 41.4° $\cos^{-1}(3/4)$ |
| $n_g d_g/\lambda$ | 0.707 | 1.22 | 1.73 |

If the structure shown in Fig. 2(a) uses *s*-transmission/*p*-diffraction gratings, the input optical beam is *s*-polarized, and the direction of this optical beam will not be altered by the input coupling holographic grating ($HG_I$). This device performs the function of "**straight**" connection (direct transmission). Similarly, the *s*-polarized optical beam from output channel will follow the same path backward and finally reach input channel. On the other hand, when the input optical beams are *p*-polarized, the input optical beam is diffracted by $HG_I$ and normally coupled out with a conjugate diffraction by the output coupling holographic grating ($HG_O$). This device performs the function of "**turn**" connection (diffraction) as shown in Fig. 2(b). The *p*-polarized optical beam from output channel will follow the same path backward and finally reach input channel, too. As shown in Fig. 2(a) and (b), these two output optical beams and the input optical beam all have the same propagation direction. Obviously, this 1×2 holographic PBS provides a bi-directional switching function; therefore, it also can be a 2×1 holographic beam combiner.

# 4 High contrast ratio optical switch with Holographic Optical Switching Elements

The optical paths of the signal and noise in a 2×2 optical switch with HOSEs are shown in Fig. 3. Fig. 3(a) demonstrates the "**straight**" state where point A connects to point C and point B connects to point D. At point C, the signal and noise powers come from point A and B, respectively. In other hand, the signal and noise powers at point D are from point B and A, respectively. A part of *s*-polarized optical power from point A passes through $HG_1$ and $HG_3$ to point C. This part of optical power is the signal at desired output channel C and its transmission efficiency is $\tau_s^2$. Another part of *s*-polarized optical power from point A will be diffracted by $HG_1$ and $HG_4$ to point D. This part of optical power is the noise of undesired output channel D and its diffraction efficiency is $\eta_s^2$. By the same reason, the signal power and noise power from point B to point D and C are $\tau_s^2$ and $\eta_s^2$, respectively. Therefore, the crosstalk ($\varepsilon$) of the 2×2 optical switch with HOSEs in the "**straight**" state can be obtained as

$$\varepsilon = \frac{\eta_s^2}{\tau_s^2}, \tag{9}$$

and the contrast ratio is

$$\mathrm{CR} = \frac{1}{\varepsilon} = \frac{\tau_s^2}{\eta_s^2}. \tag{10}$$

The theoretical values of $\tau_s$ and $\eta_s$ are shown Table 1 and the experimental values of $\tau_s$ is great than 90% and $\eta_s$ is less than 3% [5]. Therefore, its contrast ratio is greater than 900 and SNR is greater than 27 dB.

Fig. 3(b) shows the "**swap**" state of a 2×2 optical switch with HOSEs, where point A connects to point D and point B connects to point C. At point C, the signal and noise powers come from point B and A, respectively. In contrast, the signal and noise powers at point D are from point A and B, respectively. Another part of *p*-polarized optical power from point A passes through $HG_1$ and $HG_3$ to point C. This part of optical power is the noise at undesired output channel C and its transmission efficiency is $\tau_p^2$. The other part of *p*-polarized optical power from point A will be diffracted by $HG_1$ and $HG_4$ to point D. This part of optical power is the signal of desired output channel D and its diffraction efficiency is $\eta_p^2$. By the same reason, the signal power and noise power from point B to point C and D are $\eta_p^2$ and $\tau_p^2$, respectively.

Therefore, the crosstalk ($\varepsilon$) of the 2×2 optical switch with HOSEs in the "**swap**" state can be derived as

$$\varepsilon = \frac{\tau_p^2}{\eta_p^2}, \tag{11}$$

and the contrast ratio is

$$\mathrm{CR} = \frac{1}{\varepsilon} = \frac{\eta_p^{\;2}}{\tau_p^{\;2}}. \tag{12}$$

The theoretical values of $\tau_p$ and $\eta_p$ are shown Table 1 and the experimental values of $\tau_p$ is less than 3% and $\eta_p$ is great than 90% [5]. Therefore, its contrast ratio is greater than 900 and SNR is greater than 27 dB, too. This value is not high enough to completely support all applications in optical communications. For achieving this purpose, dilated optical switch has been proposed. However, it needs four basic optical switches.

For solving this problem with a single optical switch, we propose a 2×2 high contrast ratio optical switch. Fig. 4 shows a 2×2 high contrast ratio optical switch with HOSEs, and the optical paths of the signal and noise are shown also. Fig. 4(a) demonstrates the "**straight**" state, where point A′ connects to point C′ and point B′ connects to point D′. At point C′, the signal and noise powers come from point A′ and B′, respectively. In other hand, the signal and noise powers at point D′ are from point B′ and A′, respectively. A part of *s*-polarized optical power from point A′ passes through $HG_1$, $HG_3$, $HG_5$, and $HG_7$ to point C′. This part of optical power is the signal at desired output channel C′ and its transmission efficiency is $\tau_s^4$. Another part of *s*-polarized optical power from point A′ will be diffracted by $HG_1$, $HG_3$, $HG_5$, and $HG_8$ to point D′. This part of optical power is the noise of undesired output channel D′ and its diffraction efficiency is $\eta_s^4$. By the same reason, the signal power and noise power from point B′ to point D′ and C′ are $\tau_s^4$ and $\eta_s^4$, respectively. Therefore, the crosstalk ($\varepsilon'$) of the higher contrast ratio 2×2 optical switch with HOSEs in the "**straight**" state can be derived as

$$\varepsilon' = \frac{\eta_s^{\;4}}{\tau_s^{\;4}}, \tag{13}$$

and the contrast ratio is

$$\mathrm{CR}' = \frac{1}{\varepsilon'} = \frac{\tau_s^{\;4}}{\eta_s^{\;4}}. \tag{14}$$

With the same values of $\tau_s$ and $\eta_s$, its contrast ratio is greater than 810000.

Fig. 4(b) shows the "**swap**" state of a 2×2 optical switch with HOSEs, where point A′ connects to point D′ and point B′ connects to point C′. At point C′, the signal and noise powers come from point B′ and A′, respectively. In contrast, the signal and noise powers at point D′ are from point A′ and B′, respectively.

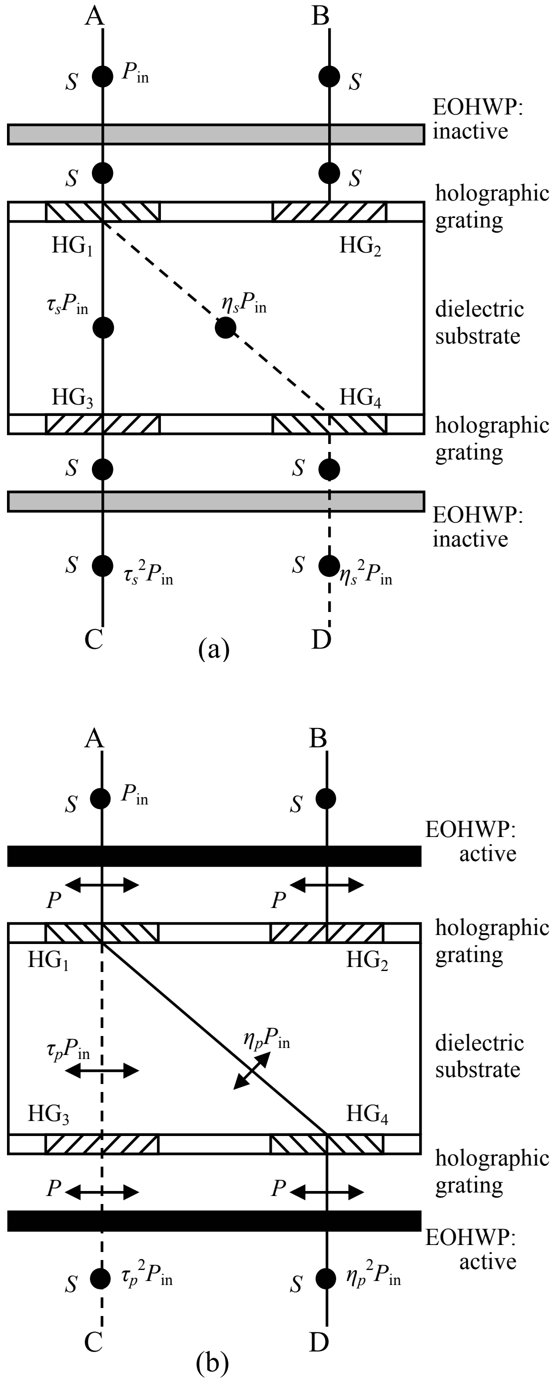


Fig. 3 The crosstalk in holographic optical switch: (a) Straight state; (b) Swap state, where HG and EOHWP are holographic grating and electro-optic halfwave plate.

Another part of *p*-polarized optical power from point A′ passes through $HG_1$, $HG_3$, $HG_5$, and $HG_7$ to point C′. This part of optical power is the noise at undesired output channel C′ and its transmission efficiency is $\tau_p^4$. The other part of *p*-polarized optical power from point A′ will be diffracted by $HG_1$, $HG_3$, $HG_5$, and $HG_8$ to point D′. This part of optical power is the signal of desired output channel D′ and its diffraction efficiency is $\eta_p^4$. By the same reason, the signal power and noise power from point B′ to point C′ and D′ are $\eta_p^4$ and $\tau_p^4$, respectively. Therefore, the crosstalk ($\varepsilon'$) of the higher contrast ratio 2×2 optical switch with HOSEs in the "**swap**" state can be derived as

$$\varepsilon' = \frac{\tau_p^{\ 4}}{\eta_p^{\ 4}}, \tag{15}$$

and the contrast ratio is

$$\mathrm{CR}' = \frac{1}{\varepsilon'} = \frac{\eta_p^{\ 4}}{\tau_p^{\ 4}}. \tag{16}$$

With the same values of $\tau_p$ and $\eta_p$, its contrast ratio is greater than 810000, too. In this 2×2 high contrast ratio optical switch, its contrast ratio has been increased from 900 to 810000, and the SNR can be raised from 27 dB to 54 dB. This SNR improvement of this device is the same as a dilated optical switch.

# 5 Conclusions

A 2×2 optical switch composed of holographic optical switching elements has been proposed previously. Its principles have been reviewed firstly. In this basic optical switch, the contrast ratio is greater than 900 (27 dB). For providing high contrast ratio, dilated optical switch has been proposed previously, where the contrast ratio has been increased from $1/\varepsilon$ to $1/\varepsilon^2$. Its signal-to-noise ratio has been doubled from $|X|$ to $2|X|$ dB. However, this 2×2 dilated optical switch consists of four 2×2 basic optical switches.

A 2×2 high contrast ratio optical switch composed of holographic optical switching elements has been presented to get high contrast ratio in a single optical switch. This switch consists of two electro-optic halfwave plates, four layers of holographic gratings, two dielectric substrates, and one spacer. In this optical switch, the contrast ratio has been increased from 900 to 810000, and the signal-to-noise ratio can be doubled from 27 dB to 54 dB. This SNR improvement of this device is the same as a dilated optical switch.

# 6 Acknowledgement

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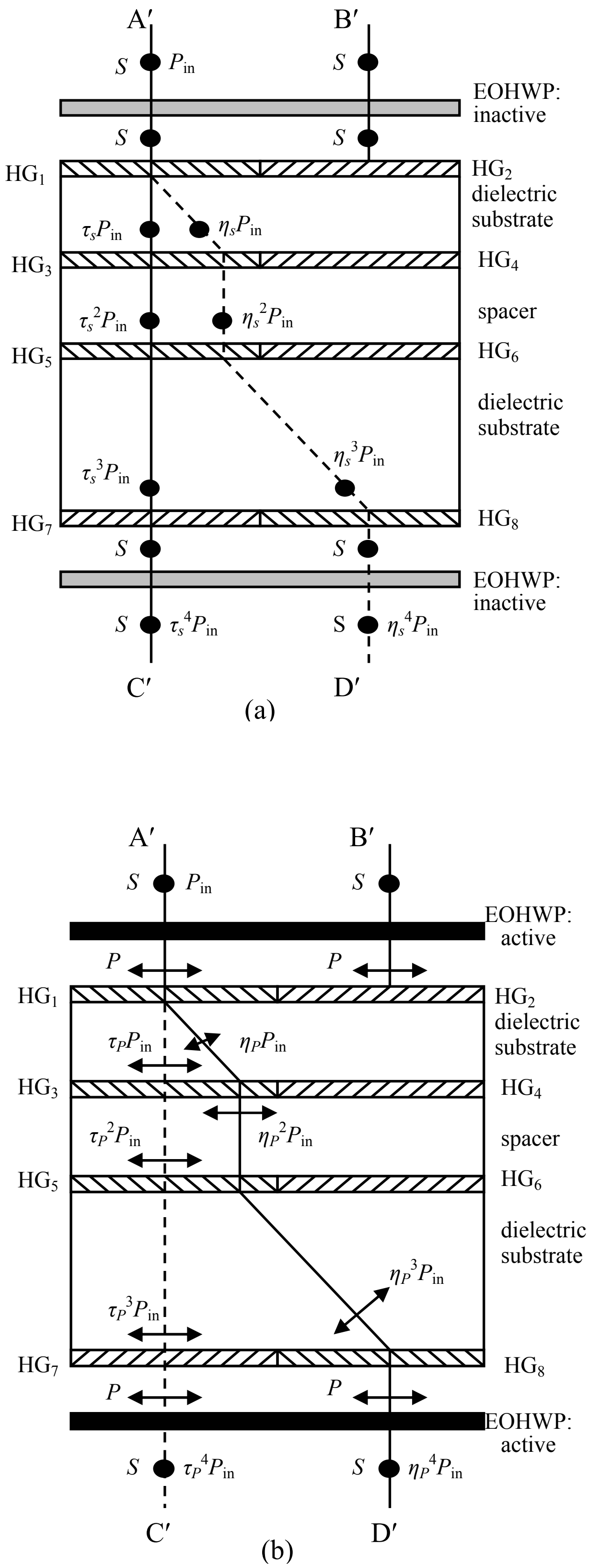


Fig. 4 The crosstalk in high contrast ratio holographic optical switch: (a) Straight state; (b) Swap state.

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