Optical Switches Using Beam Steering by Computer Generated Hologram

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Abstract

We describe a computer generated hologram (CGH) method that is applicable to a multiple input and multiple output (MxN) optical switch based on liquid crystal on silicon (LCOS). The optics of the conventional MxN optical switch require multiple spatial light modulations. In addition, a phase pattern designed using the CGH method achieves a simple MxN optical switch with a single spatial phase modulation. Moreover, the intrinsic loss of the proposed MxN switch from beam splitting can be reduced by routing multiple signals with a single knob control. We demonstrate a 4x4 wavelength selective switch and a 2-degree reconfigurable optical add/drop multiplexer switch based on the above CGH method. The experimental results indicate that these switches work well with a crosstalk of < –20.0 dB.

Keywords: hologram, optical switch, LCOS

1. Introduction

In optical communication networks, wavelength selective switches (WSSs) [1, 2] are used to achieve wavelength provisioning. WSSs can route a specific wavelength channel in a wavelength division multiplexing (WDM) system in any direction without interrupting the remaining channels. WSSs with free-space optics are widely used in networks in order to achieve a high port count and low crosstalk. An optical system of a typical WSS with one input and multiple output ports (1xN) is shown in **Fig. 1** [1, 2]. Liquid crystal on silicon (LCOS) is used for the switching engine. The WDM signals from the input port are demultiplexed by the grating, and each wavelength channel is focused at a different position on the LCOS. The LCOS modulates the wavefront of an input beam at each wavelength channel independently by using pixels arranged in two dimensions. After the wavefront is modulated, the beams are multiplexed by the grating and then connected to one of the output ports. The spatial phase pattern for the modulation controls the diffraction angles of input beams. Therefore, the focus point on a line with output ports can be controlled by such patterns, leading to port switching. In these optics, multiple signals with the same wavelength input from other ports are focused at the same position with different incident angles and modulated by the same phase pattern on the LCOS. Therefore, a WSS cannot control multiple incoming signals with the same wavelength independently.

Multiple input and multiple output (MxN) optical switches have been studied recently as a way to achieve flexible switching [3, 4]. The MxN switch can route multiple signals from multiple directions with one module. For example, a multi-degree reconfigurable optical add/drop multiplexer (ROADM), which needs the MxN switching function, can be realized by using multiple 1xN WSSs and splitters [5]. A 4-degree ROADM node with a broadcast-and-select (B&S) configuration is shown in **Fig. 2**. This configuration requires four 1xN WSSs and four splitters, which is costly and requires a lot of space. The conventional approach to the MxN optical switch is a multiple beam-steering configuration. However, the optics of such a switch are more complex than those of the 1xN WSS, which increases the size and cost. In

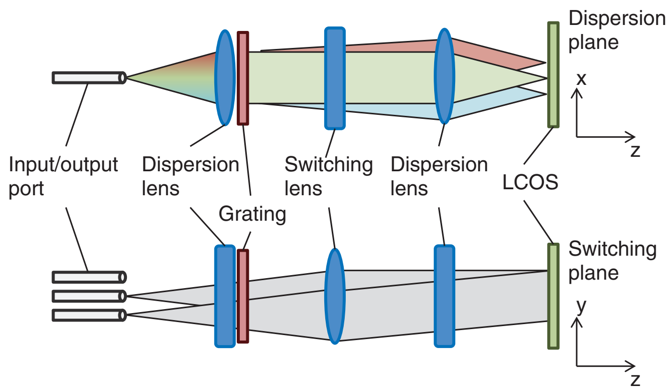

Fig. 1. Optical system of 1xN WSS.

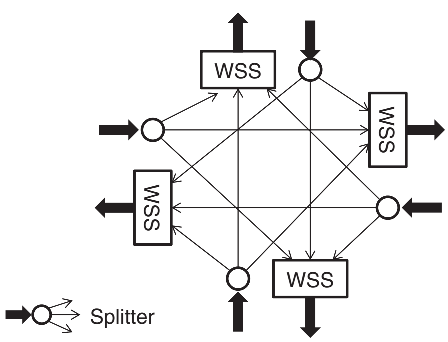

Fig. 2. Schematic of 4-degree ROADM node with B&S configuration.

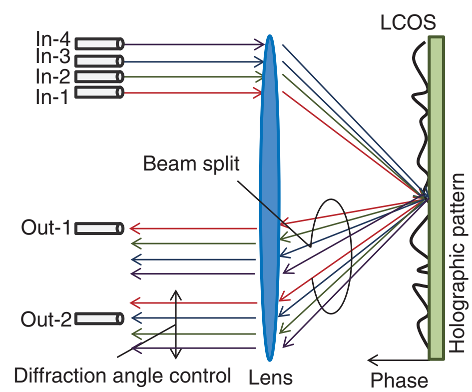

Fig. 3. Optical configuration of 4x2 optical switch based on CGH.

this study, we added the MxN switching function to the 2-f optics by using a hologram method.

2. MxN optical switch using holographic phase modulation

Our MxN switch integrates the B&S function by using holographic phase modulation. The B&S function can be divided into beam splitting (broadcast function) and port selecting (select function). In LCOS 2-f optics, the broadcast function refers to the diffraction of an input beam into multiple angles. The select function refers to the control of the diffraction angle by the phase modulation on the LCOS. If these two functions can be integrated, a B&S type MxN switch can be achieved with the 2-f optics. Holographic phase modulation can achieve both of these functions with 2-f optics. In this study, the spatial phase pattern on the LCOS was designed by using the computer generated hologram (CGH) method. In the calculation of a CGH, the phase pattern is randomly modified along the switching axis. Transmittances for designated ports are then calculated in simulations. These steps are iterated until the transmittances for the ports achieve a target value.

2.1 B&S type MxN switch

An MxN switch that integrates the B&S function via one-time holographic phase modulation has previously been proposed [6, 7]. A 4x2 switch is shown in **Fig. 3**. This switch has the same 2-f optics as the 1xN switch. In the optics, all input beams are split and diffracted at multiple angles (broadcast function). The signal beam connected to each output port is selected from each split bundle of beams by adjusting the diffraction angle (select function). The phase

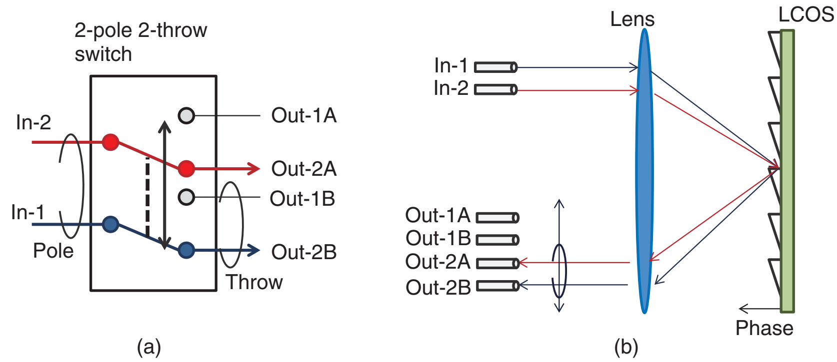

Fig. 4. (a) Switching function and (b) optical configuration of 2-pole 2-throw switch.

pattern, designed by using the CGH method on the LCOS, can split input beams into multiple angles and independently control the diffraction angle of each bundle of split beams [8]. Moreover, the connection state of multiple signals can be switched by the change in the phase pattern. As a result, an input signal from any input port can connect to any output port by using the CGH pattern.

This switch has intrinsic loss caused by beam splitting, which increases with the number of input beams. When the simultaneous switching of multiple signals is enabled, the multi-pole multi-throw (MPMT) switching function can reduce the ramification number and the intrinsic loss in the MxN switch [9].

2.2 MPMT switch array

The MPMT switch controls multiple signals in a set [10]. The function of a 2-pole 2-throw switch is illustrated in **Fig. 4(a)**. In-1 and in-2 can be connected to out-1A or out-1B and out-2A or out-2B, respectively. This switch can control the connection states of two input signals from in-1 and in-2 with a single knob control. Although the switch controls MxN ports, the intrinsic loss caused by beam splitting does not occur. The optical system of the 2-pole 2-throw switch with 2-f LCOS optics is shown in **Fig. 4(b)**. Here, the difference in the diffraction angles from the LCOS is the same as the difference in the incident angles. Therefore, if the output angle differences between the output ports are the same as those of the incident angles between the input beams, multiple input beams from multiple input ports connect to multiple output ports simultaneously by single spatial phase modulation. This is the MPMT function.

When multiple input beams are always switched in a set, the intrinsic loss from beam splitting can be reduced by using the MPMT function. For example, in ROADM networks, the same wavelength channel in the WDM system is used by received and transmitted signals connected to the same node. In other words, when an in-port and drop-port are connected, an input signal from an add-port, which is connected in the same direction as the in-port, should be connected to an out-port. In this case, these input signals from the in-port and add-port can be controlled by using the MPMT function.

The switching function of a 2-degree ROADM switch based on the 4x4 switch with MPMT function is shown in **Fig. 5(a)**. There are two connection states, that is, the add/drop state and the through state. In the add/drop state, west-in and east-in are respectively connected to the west-drop and east-drop ports. At this time, west-add and east-add are respectively connected to west-out and east-out. In the through state, west-in and east-in are respectively connected to east-out and west-out. The others are not connected to any ports. Here, the input signals in bundle-1 and bundle-2 can be controlled independently. This 4x4 switch with MPMT function can reduce the ramification number in the 4x4 switch from four to two compared with the B&S type 4x4 switch, which can independently route all input beams, resulting in a reduction of the intrinsic loss from 6 dB to 3 dB. An optical configuration of the proposed multicast-MPMT switch is shown in **Fig. 5(b)**. The configuration is the same as that of the CGH based MxN switch. We arrange the output ports so that the difference between diffraction angles equals the difference between diffraction angles connecting the out ports, leading to the MPMT function.

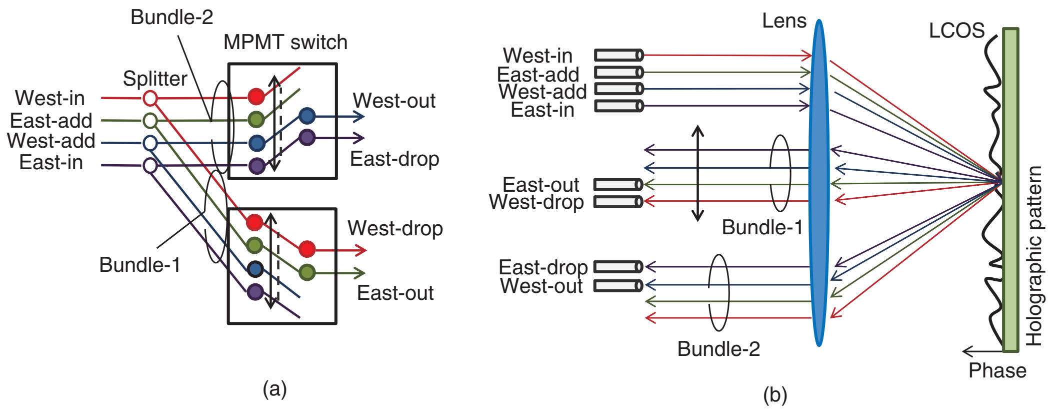

Fig. 5. (a) Switching function and (b) schematic illustration of 2-degree ROADM switch based on 4x4 switch with MPMT function.

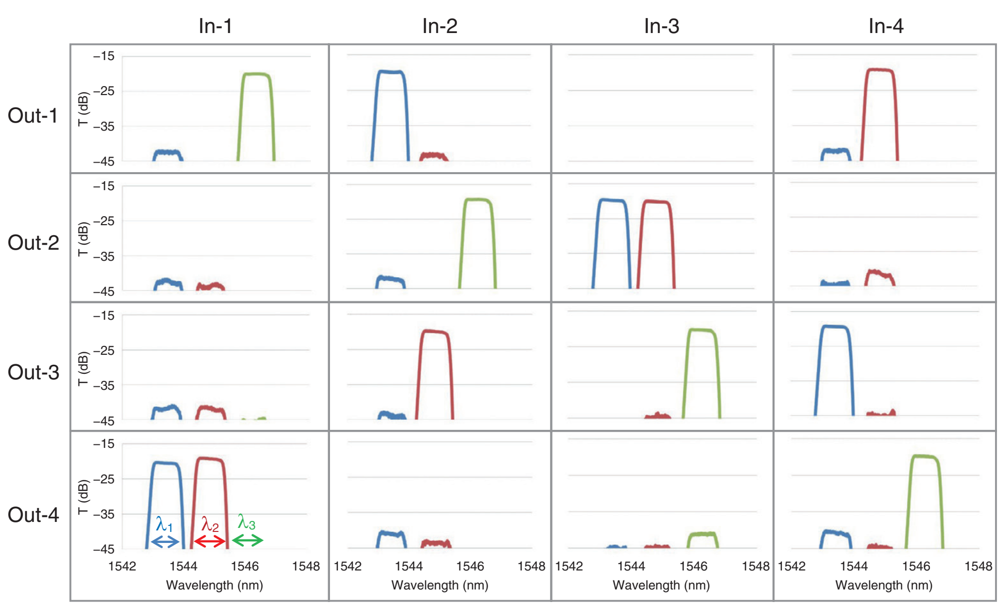

Fig. 6. Transmission spectra of B&S type 4x4 WSS based on CGH.

3. Experimental results

We describe here the experimental results for the B&S type 4x4 WSS, which can connect any input and any output ports, and the 2-degree ROADM switch with MPMT function. The patterns for spatial phase modulation on the LCOS were designed by using the CGH method [11]. The wavelength band was divided into three segments in the 4x4 WSS and two segments in the 2-degree ROADM switch. These separated wavelength bands were indexed as λ_1, λ_2, and λ_3 from short to long wavelength.

The experimental results are shown in **Fig. 6**. Diagrams lying in the same horizontal line show the measured transmittance (T) for the same output port, and diagrams lying in the same vertical line show the measured T from the same input port. Here, each wavelength channel is set in each switching state, as indicated in **Table 1**. This result shows that this 4x4 switch worked well. At this time, the maximum port crosstalk (XT) was –20.0 dB, and the increase in insertion loss above the basic level for switching was 6 dB for beam splitting and from 0.9 dB to 3.1 dB due to imperfections in the CGH.

Table 1. Connection states in experiment performed on B&S type 4x4 WSS based on CGH.

	In-1	In-2	In-3	In-4
λ_1	Out-4	Out-1	Out-2	Out-3
λ_2	Out-4	Out-3	Out-2	Out-1
λ_3	Out-1	Out-2	Out-3	Out-4

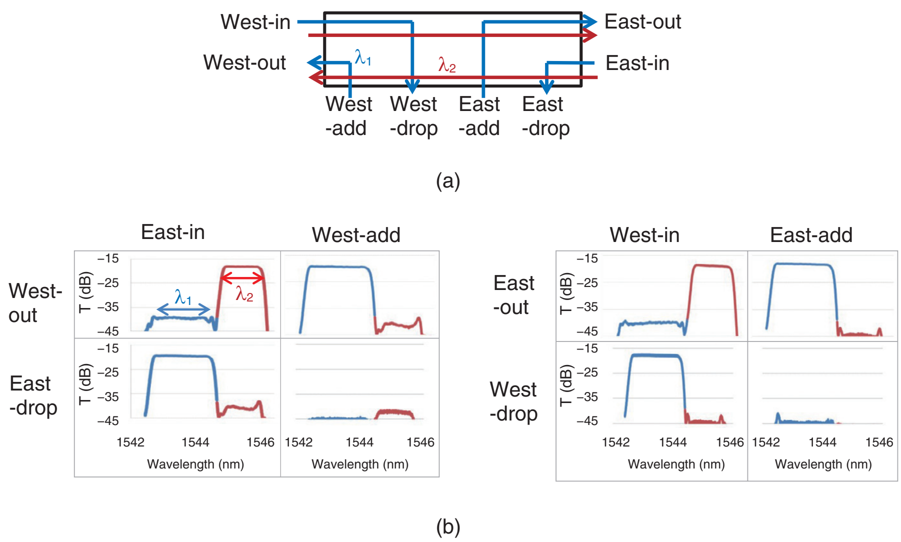

Fig. 7. (a) Connection plan and (b) transmission spectra of proposed 2-degree ROADM switch with MPMT function.

The experimental results with the 2-degree ROADM node with MPMT function are shown in **Figs. 7(a)** and **(b)**. Channels λ_1 and λ_2 were set in the add/drop and through states, respectively, as shown in Fig. 7(a). The increase in the insertion loss from the MPMT switching function was 3 dB for beam splitting and 3 dB to 4.1 dB due to the imperfection of the CGH. The maximum port XT was less than –20.0 dB.

4. Conclusion

We reported on MxN optical switches with 2-f optics. These switches use holographic spatial phase modulation for the integration of the B&S function. The switches integrate the B&S function, which can control multiple input signals independently, by using a phase modulation pattern designed using the CGH method. The CGH pattern can split input beams (broadcast-function) and control the diffraction angle of split beams (select-function). Moreover, the MPMT function can reduce the intrinsic loss of this MxN switch. We found that in a B&S type 4x4 switch without the MPMT function, the increase in insertion loss above the level for basic switching was 6 dB for beam splitting and from 0.9 dB to 3.1 dB due to imperfections in the hologram. In comparison, in a 4x4 switch with the MPMT function, the increase in insertion loss above the level for basic switching was reduced from 6 dB to 3 dB for beam splitting and from 3 dB to 4.1 dB due to imperfections in the hologram. Moreover, the crosstalk between ports was less than –20 dB.

The port XT and insertion loss can be improved by optimizing the design of the phase modulation patterns. We expect that the development of this switch will lead to new applications.

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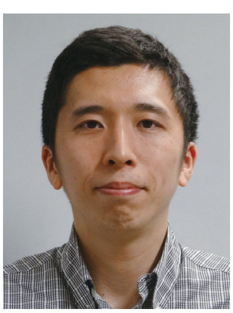

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