A Polarization-Independent Subnanosecond 2×2 Multicast-Capable Optical Switch Using a Sagnac Interferometer

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***Abstract*—We design and demonstrate a cost-effective 2×2 ultrafast multicast-capable optical switch (MCOS) based on a Sagnac interferometer. The Sagnac interferometer is composed of a $LiNbO_3$ phase modulator (PM) with two polarization-maintaining pigtail fibers and a 3-dB polarization-maintaining coupler. The MCOS works at three states: cross, bar, and multicast, in the entire C-band (1525–1565 nm) by controlling the driven voltage of the PM. Polarization- dependence is eliminated by splicing the pigtail fibers of the PM and the 3-dB coupler with 0° and 90° angles, respectively. The measured switching time is $\sim$0.6 ns. Multiple 2×2 MCOS elements can be constructed into a large nonblocking $N \times N$ MCOS matrix.**

***Index Terms*—Multicast, optical packet switch, phase modulator (PM), polarization-independent, Sagnac interferometer, ultrafast.**

I. Introduction

IN optical packet switching (OPS) networks, the payload packets are routed entirely in the optical domain. The optical switch is essentially used to transfer the payload packets from any input port to any output port. The switching time would be fast enough to route the high-speed payload, e.g., 40 Gb/s, and would be $\sim$nanosecond for 160 Gb/s [1], [2]. To date, some ultrafast optical switches have been demonstrated by employing highly nonlinear fibers [1], [3], semiconductor optical amplifiers (SOAs) [2], [4], or electrooptic crystals [5], [6]. Among them, the lithium niobate ($LiNbO_3$) electrooptic crystal is one of the best choices due to the mature arts and crafts. Its switching time is determined by the capacitance of the electrode configuration and can be subnanosecond [7]. However, it is difficult to eliminate the polarization-dependence of $LiNbO_3$ crystals in waveguided devices.

As the video streams become more and more popular, the OPS network, like its counterpart internet protocol network, would be evolved to support multicast. Most of the ultrafast optical switches previously reported have only two states: cross and bar. To achieve multicast in the optical domain, additional optical splitters are usually required to split the power of an input signal to several outputs [9], which increases the loss and cost. Yu *et al.* reported an active vertical coupler-based 4×4 optical crosspoint switch to optically implement multicast operation without extra splitting loss [5], [6]. However, the injection current has to be raised to a higher level when it works in multicast operation. By the way, its switching time is more than one nanosecond.

In this letter, we design and demonstrate a polarization-independent ultrafast 2×2 multicast-capable optical switch (MCOS) based on a polarization-maintaining Sagnac interferometer. The key component is a $LiNbO_3$ phase modulator (PM) with polarization-maintaining pigtail fibers and a 3-dB polarization-maintaining coupler, which form a Sagnac interferometer. By properly setting the driven voltage of the PM, three switching states—cross, bar, and multicast—over the entire C-band, can be realized owing to the modulation efficiency difference of the transverse-electric (TE) and transverse-magnetic (TM) modes of the PM. Subnanosecond switching time ($\sim$0.6 ns) has been achieved. Larger scale MCOS matrix can be constructed by using multiple 2×2 MCOS elements with nonblocking property.

II. Structure and Operation Principle

Fig. 1(a) shows the structure of the proposed 2×2 MCOS. The fundamental component is a $LiNbO_3$ PM inside a polarization-maintaining fiber Sagnac interferometer. The PM is designed for switching operation, which can operate in both TE and TM mode and is pigtailed with two polarization-maintaining fibers by letting its slow (S) axes aligned with the TE mode of the $LiNbO_3$ crystal substrate. Normally, the half-wave voltage $V\pi$ of the TM mode is three times higher than that of the TE mode, e.g., $V\pi(\mathrm{TM}) = 3\ \mathrm{V}\pi(\mathrm{TE}) = 18$ V in our experiment; therefore, the modulation efficiency in the two modes is different. In the interferometer, one pigtail fiber is sliced with the polarization-maintaining 3-dB coupler at 0° and the other at 90° angle, which means the S axis connected with the fast (F) axis. With the above configuration, the clockwise and counterclockwise lights transmit at TE and TM modes in the PM, respectively, and subsequently a phase difference ($\Delta\Gamma$) is generated due to the different modulation efficiencies of the two modes. And the inherent birefringence of the PM can be counteracted by the pigtail fibers; therefore, $\Delta\Gamma$ is equal to zero without driven voltage.

The phase of the clockwise and counterclockwise lights after transmitted in the interferometer loop is calculated with respect

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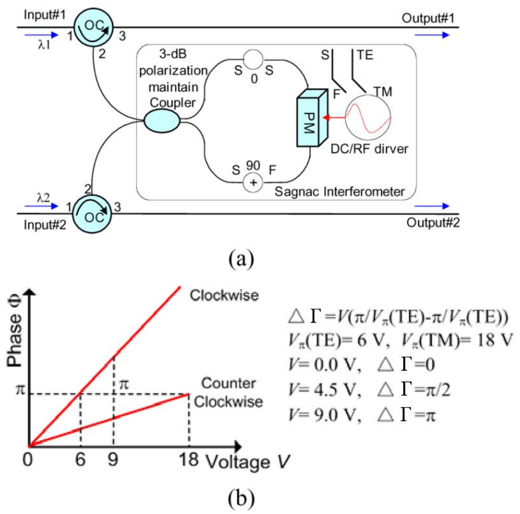

Fig. 1. Proposed 2×2 MCOS by using a Sagnac interferometer. (a) Schematic structure, and (b) phase difference of the clockwise and counterclockwise light versus the driven voltage. OC: optical circulator. S: Slow axis. F: Fast axis.

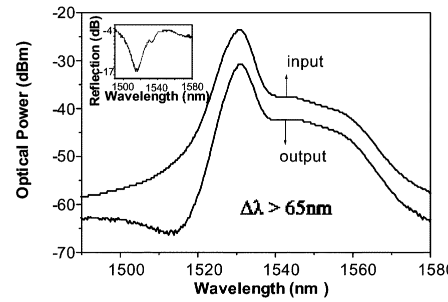

Fig. 2. Filtering effect measurement of the proposed MCOS. The two curves are the measured ASE spectrum at input#1, and output#1, respectively.

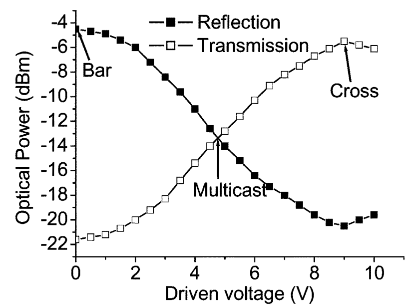

Fig. 3. Transmitted (cross state) and reflected (bar state) optical power measured at output#2 and #1 versus the driven voltage of the MCOS.

to the bias voltage of PM, as shown in Fig. 1(b). The inset includes the calculation equation and parameters. It is clear that both the phase (Γ) and the phase difference $(\Delta\Gamma)$ linearly increase with the driven voltage. The output of the Sagnac interferometer depends on $\Delta\Gamma$ according to the interference theory. For example, the input#1(2) signal is reflected by the Sagnac interferometer and then circulated to output#1(2) when $\Delta\Gamma$ is equal to 0 at $V = 0.0$ V, or transmitted to output#2(1) when $\Delta\Gamma$ is equal to π at $V = 9.0$ V, respectively. By setting $V = 4.5$ V, $\Delta\Gamma$ is equal to $\pi/2$ and the input signal is half-reflected and half-transmitted by the Sagnac interferometer and then circulated to both output#1 and #2 equally. In this case, multicast is achieved. Therefore, the MCOS can work at three states: cross, bar and multicast at $V = 9.0, 0.0,$ and 4.5 V.

Theoretically, the MCOS is polarization-independent, as depicted in [9]. The configuration of our device is similar with the polarization-independent intensity modulator described in [9], but with two important differences: 1) Polarization-mode dispersion is cancelled by setting the suitable pigtail fiber length to counteract the inherent birefringence of the PM; 2) we focus on realizing an ultrafast 2×2 optical switch with multicasting characteristic by connecting the Sagnac interferometer with two optical circulators and studying its scalability, not on designing an intensity modulator.

III. Experimental Measurement and Discussion

First, we analyzed and measured the filtering effect of the Sagnac interferometer to show the operating wave-band of the proposed MCOS. The phase difference, and hence the light transmission, is a periodic function of the wavelength λ in a birefringent Sagnac interferometer [10]. Because the slow axes of the polarization-maintaining pigtail fibers are oriented to the TE mode of the PM, the free-spectral range of the Sagnac interferometer is obtained from [10]

$$\Delta\lambda = \frac{\lambda^2}{|\Delta n_f L_f - \Delta n_{\rm PM} L_{\rm PM}|} \tag{1}$$

where Δn_f, L_f, $\Delta n_{\rm PM}$, and $L_{\rm PM}$ are the birefringence (Δn) and the length (L) of the polarization-maintaining pigtail fiber (subscript f) and the PM (subscript PM), respectively.

Fig. 2 shows the filtering effect of the MCOS without driven voltage, corresponding to the bar state. An amplification spontaneous emission (ASE) source is used to inject at input#1. The output spectrum measured at output#1 has the similar spectral shape with the input one in the whole C-band (1525–1565 nm) except for a slightly filtering effect around 1515 nm. The inset shows the reflection spectrum of the MCOS. The measured free-spectra range is larger than 65 nm, which is consistent with the theoretical calculation using the parameters in the experiment: $\Delta n_f = 3.72 \times 10^{-4}$, $L_f = 4.73$ m, $\Delta n_{\rm PM} = 7.33 \times 10^{-2}$, and $L_{\rm PM} = 2.4$ cm, corresponding to $\Delta\lambda = 67$ nm. By carefully setting the length of the PM-pigtailed fiber, the filtering effect can be totally cancelled so that MCOS is wavelength-insensitive.

We then measured the reflected and transmitted optical power at output#1 and #2 versus the driven voltage of the PM, respectively. The original input light is a continuous-wave at 1550 nm injected at input#1. The output optical powers at both output#1 and #2 are simultaneously measured with the driven voltage varying from 0.0 to 10.0 V. The results are shown in Fig. 3. The cross state happens at driven voltage of ~9.0 V and the bar state at 0.0 V. At ~4.8 V, the measured optical powers at both output#1 and #2 are equal, corresponding to the multicast state. The experimental measurement is in agreement with the theoretical prediction in Fig. 1(b) very well. The total insertion loss of the MCOS is about 5 dB, resulting from the loss of the optical circulators, the 3-dB coupler, the PM, and the splices.

The measured switching extinction ratio (ER) is about 17 dB, which is not satisfied. The predominant reason is that the splitting ratio of the 3-dB polarization-maintaining coupler is not

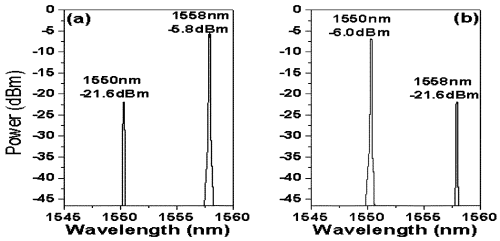

Fig. 4. Switching and crosstalk measurements.

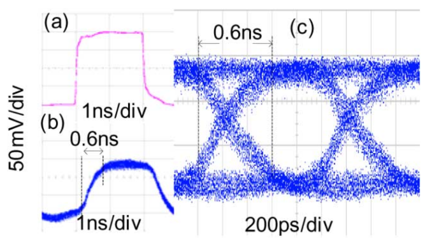

Fig. 5. Switching time measurement of the MCOS. (a) Driven voltage pulse, (b) resulted optical pulse, (c) output eye diagram of the MCOS-based intensity modulator.

exactly 3 dB, which is about 48 : 52 in our experiment. The polarization-dependent loss of the PM and the splicing errors of the fibers also slightly deteriorate the ER. With the optimization of the above parameters, the ER can be improved further. We then measured the crosstalk of the switch as shown in Fig. 4. In both "bar" and "cross" states, the desired signal is accompanied with the residual power of another channel due to the bad ER, which will induce power penalty. The crosstalk in the two states is about 15.5 dB. However, before detection, the out-of-band crosstalk can be suppressed using a narrow-band optical filter. We also measured the polarization-dependence of the MCOS. A polarization controller is inserted at input#1 to vary the polarization state of the input signal and the optical powers measured at both output#1 and #2 remain unchanged, which verifies that the MCOS is polarization-independent.

Finally, we measured the switching time of the MCOS. Note that the switching time is determined by the response time of the PM. In the experiment, the PM works up to 2 GHz. Fig. 5 shows the driven voltage pulse, the resulted optical pulse, and the eye diagram of the MCOS-based intensity modulator, respectively. The measured switching time is about 0.6 ns, which is the rise time of the optical pulses. The switching time is fast enough for routing high-speed payload, such as 160 Gb/s [2].

IV. Cost-Effective Scalability

The 2×2 optical switch is a basic element to construct a large-scale $N \times N$ switch matrix with nonblocking property. Without lack of generality, herewith we take a 4×4 switch matrix as an example. Fig. 6 is the constructed 4×4 MCOS matrix by using six 2×2 MCOS elements in Benes-type [7]. An $N \times N$ Benes-type switch matrix can be configured by $(N/2) \cdot (2 \log_2 N - 1) 2 \times 2$ switch elements, which is much more cost-effective than that made by ON–OFF SOA gates [6], where N^2 SOA gates are required. Moreover, the multicast capability is supported in the constructed switch matrix by setting

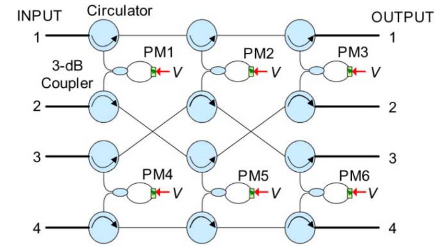

Fig. 6. A 4 × 4 MCOS matrix by using six 2 × 2 MCOS elements.

the driven voltage at the multicast state in the 2×2 MCOSs. If all the input signals have different wavelengths, the multipoint-to-point and multipoint-to-multipoint operation can also be achieved in the switch matrix by controlling the driven voltages of each constituent PMs, similar to [5] and [6].

V. Conclusion

We design a polarization-independent subnanosecond 2×2 MCOS by using a PM-based polarization-maintaining Sagnac interferometer. Three operation states of cross, bar, and multicast are realized by controlling the driven voltages of the PM. The switching time is ~0.6 ns. The filtering effect of the Sagnac interferometer is canceled so that the MCOS can work in the entire C-band. The 2×2 MCOS can be used to construct a large-scale nonblocking $N \times N$ switch matrix. Such a cost-effective, polarization-independent, ultrafast, and multicasting-capable optical switch matrix would be useful in the future OPS network.

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