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Mach-Zehnder Type Tandem Optical Switch/Modulator using a Single-Mode Interconnecting Waveguide and Its Switching Characteristics

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Abstract – In this paper, an optical switch/modulator is designed and its light propagating characteristics analyzed using a simplified BPM. The distinctive feature of this switch/modulator is that all its waveguide branches are designed as single-mode. The principle of the device is based on the coupled mode theory in the Y-junction interconnecting waveguide. In spite of the fact all waveguides are designed as single-mode, by adjusting the interconnecting waveguide length of the device the same characteristics as existing up to date devices are obtainable. Numerical results show that the switching characteristics periodically depend upon an interconnecting waveguide length with a spatial of about 150 μm in the Ti:LiNbO$_3$ step index waveguide. The design concept would therefore be utilized effectively in fabricating a monolithic high density optical integrated circuit.

Keywords: Optical switch/modulator, BPM, Waveguide design

1. Introduction

Recently, considerable progress has been made in the design and fabrication of active waveguide devices for switching and modulation in optical integrated circuits. Such devices have broad bandwidth, low driving voltage and cost, and are suitable for coupling to optical fibers [1-3]. In cases where many optical devices are integrated monolithically on a substrate, as the density of circuit integration increases, the interval between the devices becomes shorter and an undesirable mode coupling between the waveguides would appear [4-6]. The coupling disturbs the stable operation of each device and degrades their total performance. Thus, in the monolithic high density of optical integrated circuits, it is important to guide the propagation of the light wave from one device to another without undesirable mode coupling occurring [7-9].

Many types of optical switches, such as the Y-branch switch [10], the Bifurcation Optique Active (BOA) switch [11], and the TIR switch [12], have been proposed and considered by many research groups, both numerically and experimentally. However, the Y-junction combiner-divider sequence of all optical switch/modulators reported to date was the dual-mode waveguide, and operation of the device was supported by the two modes interference phenomenon in the interconnecting waveguide. Martin has also reported a branched interferometric modulator which can also operate as a switch [13]. In typical switch/modulators such as Martin's, which is shown in Fig. 1, the input and output waveguides were designed to be single-mode, while the interconnecting waveguide was dual-mode. The interconnecting waveguide of the device is broadened from single-mode to dual-mode waveguide to utilize the interference phenomena between these modes. Without widening the interconnecting waveguide width, however, the same switching characteristics as the Martin's is obtainable by adjusting the length of the single-mode interconnecting waveguide.

Therefore, the main goal of this paper is to study the optical switch/modulator in which all Y-junction power-combiner and power-divider sequences are made of a single-mode as shown in Fig. 2. The switching and modulation characteristics of the device are investigated by the BPM simulation [14-15].

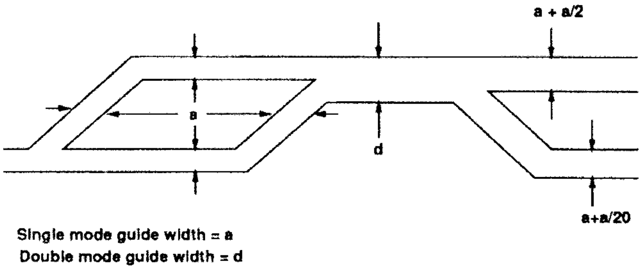

Fig. 1. Martin's interferometric waveguide switch

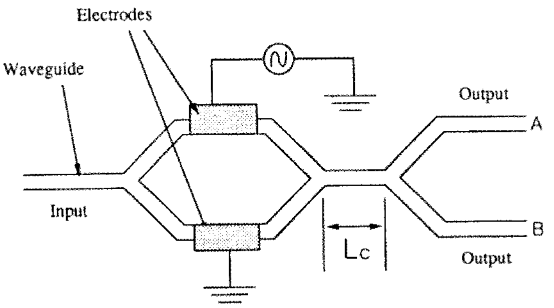

Fig. 2. Tandem Mach-Zehnder optical switch/modulator

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Successful operation of the device requires precise control of the relative phase of the optical modes and of the separation between the waveguides. From a practical point of view, a single-mode interconnecting waveguide is advantageous as its smaller width permits us to place metal electrodes more closely in optoelectronic devices, thus reducing the required voltage.

This paper is designed in the following way. In section 2, we introduce the operating principle of the single-mode waveguide switch/modulator. We describe the method of numerical analysis in section 3, and show the results of the PBM in section 4. Some concluding remarks are given in section 5.

2. Principle of the device

The waveguide structure of our designed switch/modulator is shown in Fig. 1. This device consists of an interferometric waveguide modulator and an additional Y-combiner connected by a straight waveguide. All the waveguides of the switch/modulator are of same width, and here we shall consider that they are designed only for the fundamental mode. The interconnecting waveguide acts as the optical interaction region which determines the switching characteristics of the device.

Without any modulating voltage at the electrodes, there will be no phase shift between the light waves of the two branches of the interferometer and they will recombine at the Y-combiner giving a field distribution which corresponds to the fundamental mode, and light waves past the Y-combiner will be guided. With the applied modulating voltage, there will be a phase change and if the modulating voltage is sufficient enough to produce a phase change equal to 180°, the field distribution past the Y-combiner must correspond to the pure second order mode field. However, if the phase difference lies in between these two extreme ranges (0 to π), the field distribution past the Y-combiner will show the result of the interference of the first and quasi-second order mode fields as shown in Fig. 3.

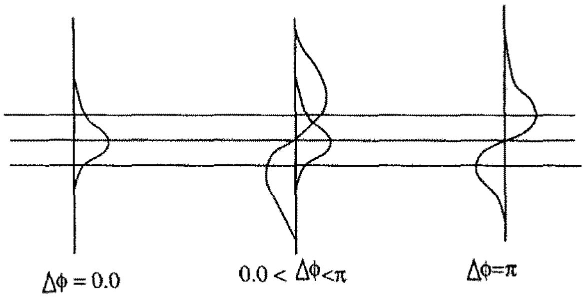


Fig. 3. Interference of the first and quasi-second order mode

If the phases of the first and quasi-second order modes are in phase, both modes will interfere and constructively enhance the light field amplitude, If they are out of phase, destructive interference will happen, thereby reducing the light field amplitude in the interconnecting waveguide. Since the phase of the second order mode will vary according to the length of the interconnecting waveguide, past an interval of the characteristic length L_c, the peak of the resultant field will change from one side of the waveguide to the other. If we add a Y-divider at the output port and adjust the length equal to the integer multiple of L_c, the light wave will choose that branch of the Y-divider whose side, at the start of branching, possess the peak field. Since the quasi-second order mode is an antisymmetric mode, the characteristic length L_c is defined as

$$L_c = \frac{\pi}{\beta_{sym} - \beta_{anti}} \tag{1}$$

where, β_{sym} and β_{anti} are the propagation constants of the symmetric and antisymmetric mode respectively. These two modes propagate with different phase velocities, so the light power of the combined field changes along the direction of propagation, reaching a maximum at one side of the waveguide and then back on the other side and so forth, depending on the length L_c. Since all waveguides are designed as single-mode, it is the major difference between our device and existing up to date devices that the quasi-second order mode is not well defined in the interconnecting waveguide. In reference [10], an interferometric modulator is made into a switch by connecting a third Y-junction at the end of the interferometer as shown in Fig. 2. In this device, the output straight interaction region is designed to support the second mode. The width of the other waveguide of the third output Y-junction was made unequal and not to support the single-mode.

3. Numerical analysis

3.1 Waveguide design

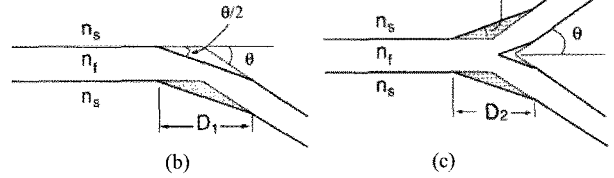


Fig. 4. Waveguide structure and design parameters

Using the BPM analysis, we have calculated the light propagating characteristics of this switch/modulator. The waveguide is considered to be made on the $LiNbO_3$ substrate with step distribution, and all of the device's waveguides were designed with a single-mode. The design structure and parameters of the waveguide is shown in Fig. 4(a). In order to reduce light power loss, the branching and bending angles of the waveguide are adjusted as shown in Figs. 4 (b) and (c). The waveguide parameters calculated by the BPM for smart operation are shown in Table 1.

Table 1. Optimized design value of the modulator

Name of parameters	Symbols	Optimized value
Dividing angle	θ	0.8deg.
Gap of waveguide	2d	26μm
Length of adjusted bent	D_1	186 μm
Length of adjusted Y-divider	D_2	408 μm
Y-divider waveguide	$L_2=L_4$	950 μm
Straight parallel waveguide	L_3	1200 μm
Interconnecting waveguide	L_c	600 μm

3.2 Modulation characteristics

Fig. 5 shows the field propagation in the waveguide after an electric field was applied. As the applied electric field at the electrodes increases, more light waves are radiated out of the guide past the Y-combiner. Because the waveguide is designed only to allow fundamental mode propagation and thus cannot support a combined field consisting of the fundamental and quasi-second order mode field.

The output power of the modulator is calculated by varying the DC bias voltage at the electrodes. The obtained characteristic is shown in Fig. 5. From this figure we also found the V_π voltage equal to 1.8 volt/μm. The propagating pattern of the waveguide was shown in Fig. 6. At voltage $V_\pi = 1.8$ volt/ μm, for which the total phase shift is equal to π, no power is confined in the waveguide as shown in Fig. 6(b), because the combined field has now completely become a second order mode.

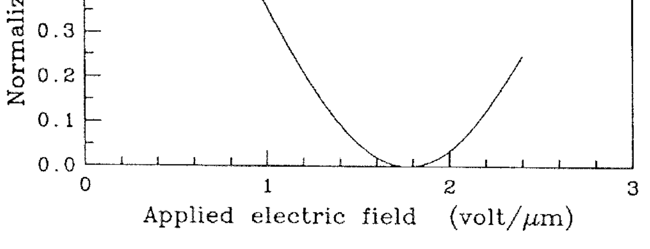
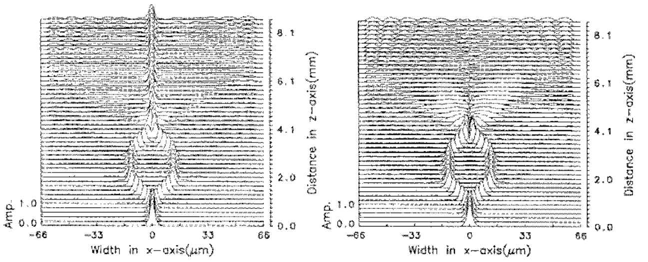


Fig. 5. Half wave voltage of the modulator

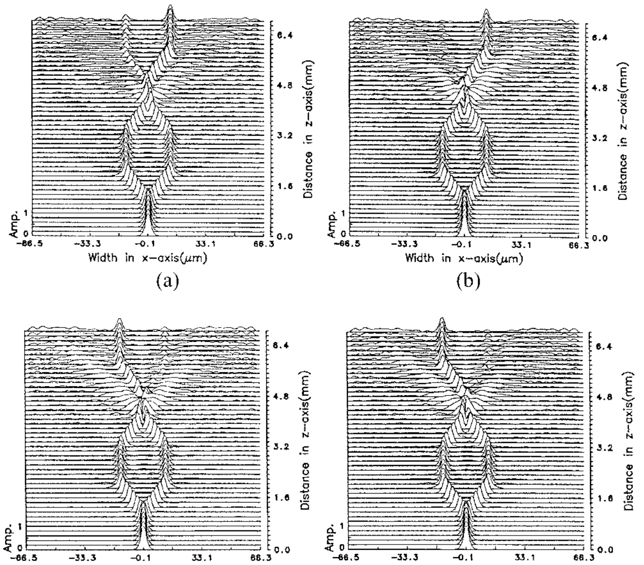


(a) 0.8volt/μm (b) 1.8 volt/μm

Fig. 6. Light field propagation in the first stage of the switch with the variation of the applied electric field

3.3 Switching Characteristics

Changing the switching voltage, the light field propagation through the switch is shown in Fig. 7. For switching voltage V_π, power shifts from one branch to the other (Figs. 7(c) and (f)). But, with the switching voltage equal to $V_\pi/2$, light fields divide equally even though there is a lot of radiation. From Eq. (1), the characteristic length L_c was found at 620μm. With the BPM, we calculated the output light power by varying the switching voltage keeping the length of the interconnecting waveguide L_c as the parameter (see Fig. (8)). From these figures, we found that the characteristic length is about 600μm, which is very close to the theoretical value.



(a) (b)

(c) (d)

Fig. 7. Light field propagation of the switch with the variation of the applied electric field.

4. Experiments

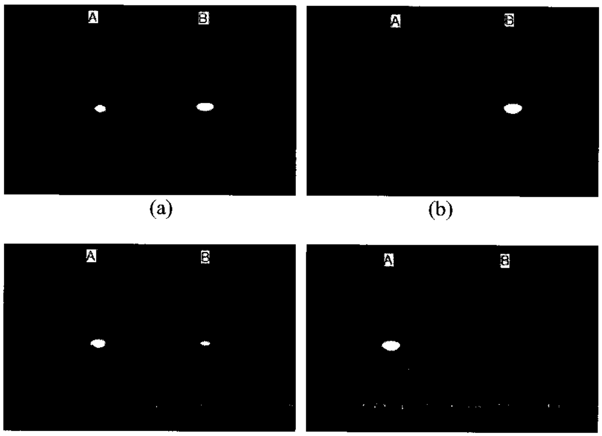
4.1 Device fabrication

The switch/modulator shown in Fig. 2 was fabricated onto a Z-cut $LiNbO_3$ substrate. We made the symmetric waveguide by evaporating 30nm of Ti on the substrate. The Ti was patterned using photolithography and chemical wet etching. The Ti was diffused into the substrate at 1000 for 5 hours with flowing O_2 which had been passed through pure water in order to reduce surface waveguiding. A 150nm buffer layer of SiO_2 was sputtered onto the substrate prior to the electrodes being deposited. The electrodes were deposited by evaporating 200nm of Al onto the buffer layer and patterning it using photolithography and chemical wet etching. The electrode lengths were 1250μm, the gap was 30μm and the width was 10μm. The substrate edges were optically polished to connect a polarization-maintaining optical fiber.

4.2 Experimental results

In order to validate the technique described in the previous sections, we applied a modulation voltage directly to the electrodes from 0 (zero) to 2 volts. The output power pattern of each branch is shown in Fig. 8. As is expected in the design of a waveguide, the half wave voltage is about 2.0volt/μm. The extinction ratio, i.e. the ratio between the on and off power of the switch, was about 10dB at $V = \pm 2.0$ volt for 1mW input power.

The experimental results are in good agreement with the numerical analysis shown in Fig.7.



(a) (b)

(c) (d)

Fig. 8. Output power pattern of each branch

4.3 Discussions

The switching characteristics are decided with the length of the interconnecting waveguide as shown in Eq. (1). We investigated the switching characteristics with the variance of the length of the interconnecting waveguide. The effect of periodic phase reversal is illustrated in Fig. 9. The switching behaviour found at $L_c = 750$ μm also looks like the curves at $L_c = 600$ μm. The results indicate that the light power transmitted to the output waveguide branches is a periodic function of the interconnecting waveguide length L_c, with a spatial period of about 150μm. Comparing the curves at $L_c = 600$ μm and $L_c = 1200$ μm, we see that light intensity decreases in the guide and gradually decays as it propagates through the outer straight waveguide. Since the width of the outer straight waveguide is for the single order mode, the relative light intensity in each branch was less than 0.7.

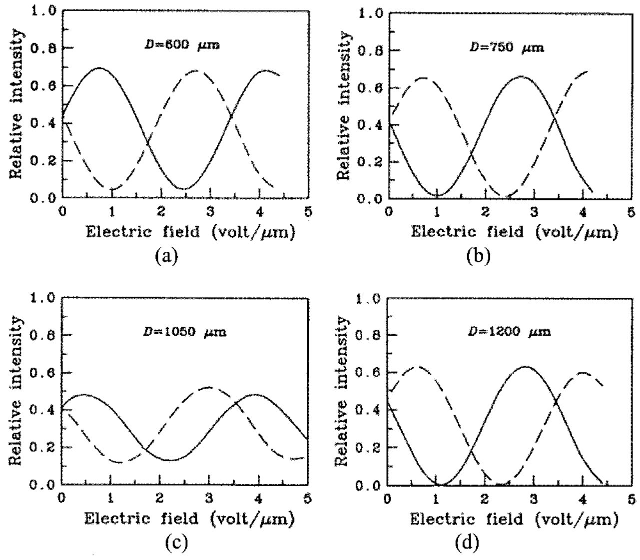


Fig. 9. Output power versus switching voltage with a parameter L_c : the solid line represents the power of one branch and the dashed line represents the other branch.

5. Conclusion

We have designed a two cascaded Mach-Zehnder switch/modulator in which all waveguides are single-mode, and investigated light propagation through the single-mode interconnecting waveguide structure by means of a simplified 2-D BPM.

The numerical results elegantly showed the aspects of switching and propagating of the light wave. Even though the interconnecting waveguide is made of a single-mode, we should realize the same characteristics as the dual-mode waveguide by adjusting the length of the interconnecting waveguide. The switching principle is based on mode coupling within the interconnecting waveguide. The results also indicated that the switching characteristics are an oscillatory function of the interconnecting waveguide length with a spatial of about 150μm. We have also showed that the dual-mode interconnecting waveguide is not necessary to achieve an unequal light power splitting in the Ti:$LiNbO_3$ waveguide devices.. The same effect is obtainable with a single-mode interconnecting waveguide. Smaller waveguide width offers the possibility of reducing the driving voltage in optical integrated devices.

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