LiTaO$_3$ Directional Coupler Switch with Enhanced Extinction Ratio and Low Insertion Loss

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Abstract: A novel design of optical directional coupler switch with S-bend waveguides on LiTaO$_3$ platform has been designed with R-Soft CAD tool and the same is simulated by Beam propagation method (BPM) for light propagation analysis. The simulation results of the optical directional coupler (ODC) switch is reported. We observed that the directional coupler (DC) switch has lower insertion losses and higher extinction ratios for a certain values that are discussed in the paper. This was studied by variation in waveguide parameters such as, wavelength, waveguide gap, and length of the device. Simulation results designate that the switching efficiency for TE and TM modes with extinction ratio about 3dB when the waveguide gap is 3.5μm for both the polarization modes and insertion loss is 13dB with same waveguide gap in TE mode and 16dB in TM mode at 1550nm wavelength.

1. Introduction

Lithium Tantalate (LiTaO$_3$) being one of the promising material for nonlinear optical devices as it has a good threshold to optical damage. An optical directional coupler (ODC), or an optical coupler in short is a useful component as in an optical modulator and an optical switch in an optical integrated circuits. Optical switches are one of the functional components in any optical networks for routing, protections switching, cross connections, add-drop multiplexers, optical modulators, and ring resonators [1]. They lead an significant role due to their high performance such as low propagation loss, high extinction ratio, better scalability, and low waveguide coupling loss [2-3] which are very much required for switching. ODCs are one of the essential components in integrated photonic circuits which can be used as various optical devices such as wavelength filters, polarization converters, MUXs/DEMUXs, optical switches etc. Directional couplers are conveniently employed in the design of all optical integrated circuits including optical switches/modulators [4]. The optical coupling between the two waveguides in the directional coupler is dependent on the coupling length, coupling distance, width of the core, wavelength and other waveguide parameters.

2. Design of optical switch

The 3-D structure of the ODC device is shown in Fig. 1. The 2 waveguides in structure are separated by 20μm at the input and output ports. The S-bend waveguides are used instead of straight bend for more efficiency. The total length of the device is 2.7cm. The other parameters include input power of 1μW, the width of the devices is varied from 3μm to 6.5μm, the coupling length between the coupling...
waveguides is 10000μm, free space wavelength is 1.55μm, waveguide separation is 3μm, under both TM and TE polarization modes on LiTaO₃ substrate. The schematic design of the proposed optical directional coupler switch along with propagation of light and mode profiles is shown in Figure.1.

![Figure 1](image)

**Figure 1** (a) Design and launching fields of the ODC, (b) Mode profile of the ODC, (c) propagation direction of the ODC with slice approach, (d) propagation of light view throughout the ODC.

The device structure consists of two straight waveguides and four S-bend waveguides. The Simulation of symmetrical ODC by beam propagation by the variation of width from 3μm to 6.5 μm, at 1550 nm wavelength is done. Both waveguides are single-mode waveguides. The gap in coupling region in the middle is 3 μm wide between the coupling waveguides. Outside the coupling region as the mode fields really don't touch each other the coupling is negligible. With numerical beam propagation method, the injection of light at the input port1 and propagation of light into other port after coupling can be observed.
Figure 2 (a) 3-D view of launching field and the Amplitude distribution in a coupler
(b) 3-D view of launching field of optical switch by optical directional coupler (ODC) with 2-outputs

Figure 2 (a) & (b) are obtained with a simulation by beam propagation method after the design by R-Soft CAD tool. [5]. In this particular situation, the light first propagates through the first waveguide and couples almost entirely to the second waveguide after a short distance and finally comes out of the second output and most of the power remains there. It evidently reveals that the change parameters like in width enables the change in polarization light traversing through the waveguide medium interacts with it which is proportional to the intensity of the field.

3. Effect of Width (W)

The width of the symmetrical optical directional coupler is a basic parameter to influence the polarization within the guiding layer. The changes of coupling ratio and extinction ratio are found to be very sensitive to the component width of the directional coupler, which is shown in Figure 3. From this Figure 3 the coupling ratio is observed to decrease with increase in component width. This is above 90% at 3μm and 6.5μm of the component width for symmetrical optical directional coupler for output-I in TE polarization. This is because the higher widths enable the higher mode of confinement of the light. The Extinction ratio of both TM and TE polarization through the output-I is gradually being increased with increasing the component width of the optical directional coupler. at the same width it becomes the maximum value (0.02dB) because of the coupling efficiency of the TM mode.

Figure 3. Plot of coupling ratio and Extinction ratio of Directional Coupler with variation of component width
4. BPM simulation results

Recently BPM is the most prominent method and very widely used propagation technique for investigating both linear and as well as nonlinear light-wave phenomena in axially varying waveguides in photonic devices. The BPM is essentially a meticulous approach for approximating the exact wave equation for monochromatic waves, and numerically solving the resulting equations. The basic approach is illustrated by formulating the problem under the restrictions of a scalar field (i.e. neglecting polarization effects) and paraxiality (i.e. propagation restricted to a narrow range of angles). By the Beam Propagation Method (BPM) this simulation was also carried for propagation of optical signals through the symmetrically designed optical directional coupler for fundamental TM and TE modes [6]. The corresponding simulated amplitude distribution is shown in Figure 2. The Figure 3. shows the plot of coupling ratio and Extinction ratio of ODCs with variation of component width giving the results at 1550nm in the form of graphs. The formulae for calculating extinction ratio (ER) and coupling ratio (CR) are as following.

\[
ER_{TM} = 10 \log_{10} \frac{P_{TM}}{P_{TE}} \text{dB}
\]

\[
ER_{TE} = 10 \log_{10} \frac{P_{TE}}{P_{TM}} \text{dB}
\]

\[
CR = \frac{P_2}{P_1} = \frac{\text{output Power at coupled waveguide}}{\text{Input Power}}
\]

Where ER is the Extinction ratio (dB) of an ODC which can be defined as the ratio between the transmitted powers of two polarizations from same output port. \(P_{TM}\) is the transmitted power at TM-mode, \(P_{TE}\) is the transmitted power at TE-mode.

5. Transmitted Power with Insertion Loss as a function of Variation in Width

Though coupling strength depends sensitively on many parameters like the wavelength, gap between the coupling waveguides, length of coupling waveguides. The width of the waveguides also impacts a lot. The transmitted power in the out port ports switches by the variation of the width of the waveguide. The insertion loss is calculated to the transmitted power and shown in the graph in Figure 4. The simulated Transmitted power dependence for both TE and TM modes is shown in Figure 4.

![Graph showing Transmitted Power with Insertion Loss as a function of component width.](image)

Figure 4 Transmitted Power with Insertion Loss as a function of component width.

6. Results and Discussion

Figure 4 shows the transmitted power of the optical switch with insertion loss in TE and TM mode. It is observed that insertion loss with the port-2 (coupled) has maximum insertion loss of 3dB for both TE and TM modes. Switching phenomenon was observed which is shown in Figure 1 simulation.
profile. The extinction ratio was observed 6dB in TE and TM modes. The switching phenomenon was observed at port-2 because of the coupling of the waveguide at 1550nm wavelength. Insertion loss is the amount of power loss in the signal in coupling to the output port is special criteria for estimating the switching phenomena.

7. Conclusions
In summary, in this paper a symmetrical optical directional coupler switch was proposed which is exhibiting switching phenomena with a change in width of the waveguides of the device. It is found from BPM simulation results that extinction ratio can be increased by choosing proper waveguide parameter such as wavelength, wavelength, waveguide gap and width, and at the same time insertion loss can be reduced. This symmetrical optical directional coupler switch can be used as key components for integrated optical communication devices and useful for build up functional devices. This work supplies a capable solution for all optical directional couplers on a LiTaO₃ platform.

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