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Nine bit Mach Zehnder Interferometer based Comb Shaped Optical True Time Delay Line for Antenna Beam forming

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***Abstract*—A nine bit comb shaped delay line consisting of Mach Zhender Interferometer (MZI) and MMI coupler is realized on Silicon platform at 1550nm.The device spans 35µm and offers a variable delay from 5fs to 40fs.Simulated Insertion loss of the device is -25dB. FDTD method is used for the analysis. The delayed signal is fed to the antenna array and the variation in the radiation pattern is observed.**

Keywords—Mach Zehnder Interferometer(MZI),Optical True Time Delay line, Antenna beamforming

I. INTRODUCTION

A Mach Zehnder Interferometer modulator is used for controlling the amplitude of an optical wave. When a voltage is applied across one of the arms, the phase shift is induced for the wave passing through that arm [1].When the two arms are recombined the phase difference between the two waves is converted to an amplitude modulation. This property is exploited to design the optical delay lines sensors, Optical Add drop multiplexers (OADM), Optical Cross connects and switches.

The recent research shows that MZI is an integral part of Microwave Photonics where optical signals controls the microwave [2] and millimetre waves. Broadband and low loss capability of photonics has enabled to control and distribute microwave and millimeter waves for applications such as Broad band, wireless, Access network, sensor network, radar satellite, communications, instrumentation and warfare system.

Photonic technology is an attractive solution to the problem associated with distribution and processing of millimeter and microwave signals in modern phased array antennas [3].The photonics devices are mostly fabricated on silica.

Silica based devices have relatively large dimensions due to the low index contrast and the corresponding large bending radius of the fiber matched waveguides[4].Silica on insulator(SOI) is an attractive technology in the current research. SOI combines large area and low cost silicon substrate technology with high delay per length ratio available in semiconductor waveguides technology (n=3.46).Further the SOI waveguides exhibit low losses of (0.1-0.2) dB per centimeter [5].

The types of optical true time delay lines used for beam forming, optical computer tomography (OCT) are fiber based delay line, optical MEMS based TTD, Polymer waveguides, Ring resonator,PCF based TTD,Delay lines on silicon chip,MZI based TTD,Optical Mux/Demux,Photonic crystal based delay line, Sub wavelength grating enabled ultra compact on chip TTD [6]-[13].

In this paper a comb-structure delay line is presented. The device comprises of asymmetric MZI in conjunction with a comb to provide variable delay in femto seconds.The delay obtained is fed to the antenna array and the radiation pattern obtained is observed ensuring wide coverage of targets.

This paper consists of six parts 1) Introduction 2) Design and Analysis 3) Principle of operation 4) Applications 5) Simulation Results 6) Conclusion and future scope.

II. DESIGN AND ANALYSIS

A. The schematic diagram of the proposed Nine bit Mach Zehnder Interferometer based Comb shaped Optical TTD line for Antenna beam forming.

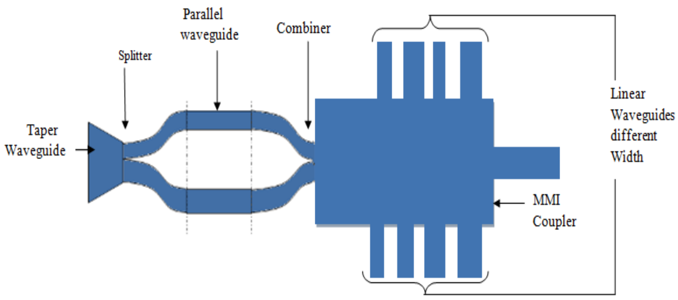


Figure1: Nine bit MZI based Comb shaped Optical TTD

B. The building block

silica based ridge waveguide is depicted in the Fig.2

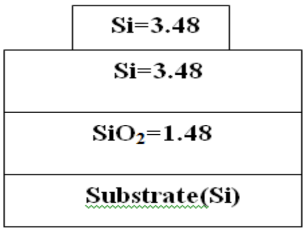


Figure 2:SOI Ridge waveguide

C. Design

Figure 1 illustrates the working principle of the Nine bit Mach Zehnder Interferometer based Comb shaped Optical True Time Delay. The proposed device consists of taper waveguide, Mach-Zehnder interferometer switch with asymmetrical width of upper and lower arm, multimode interference coupler and nine linear waveguides of different widths. Delay is observed at different points of different linear waveguides. Waveguide one is taken as a reference waveguide. The proposed device is based on ridge type waveguides with height of 4.74µm, a slab thickness of 4µm and width is 3µm of wide waveguide delay line. Upper arm of MZI switch is 2µm wide and lower arm is 2.5 µm wide. Multimode interference coupler is 20µm long and 11.25µm wide. Taper waveguide 8µm wide and 4µm long.

Nine linear waveguides are used. As shown in Fig.4.They vary in their width ranging from 1.5µm to 2.5µm.(All dimensions are in µm) and the length varied from 1 to 9µm. The device is designed to operate in the transverse-electric (TE) polarization.

D. Schematic diagram of Nine bit MZI based Comb shaped Optical TTD line

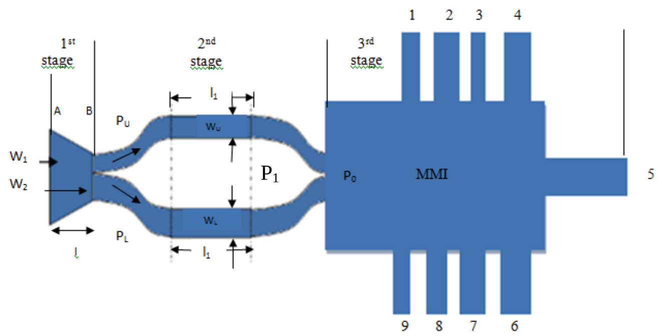


Figure 3: Schematic diagram of Nine bit MZI based Comb Shaped Optical TTD line

E. Theoretical Analysis

Consider the Fig.3 depicted above
Input Width = W1

Output Width = W2

Input power to the taper = P_1

"l" is the length measured from point "A"

$$\text{Power at B} = P_1 \, e^{-jwl =} P_2 \qquad (1)$$

Assuming the power distribution inside the taper.

Power coupled to the MZI is $P_{3.}$

The coupling loss at 'B' is (P_3-P_2)

$$I_L = P_3\text{-}P_2 \text{ dB} \qquad (2)$$

Power supplied to the upper arm is $P_{U.}$

Power supplied to the lower arm is P_L

$P_{U\,\alpha}\, \Delta\, \omega i$ i= 1, 2

$P_L = k\, \omega_2$ Where 'k' is the coupling coefficient

When the signal in the upper arm and lower arm are in phase maximum power is coupled to the output MMI coupler. Since there are no electrodes across the arm 180^0 phase shift between the upper and the lower arm is not present. The two asymmetrical arms of the MZI produces delay Δt. The delay Δt α ω (Width of the MZI straight arm) Further delay can be achieved if an electrode is placed along the lower arm of MZI.

The output power:

$P_O = P_U$ -(Losses in the upper arm)

$= [P_U - L_U] + P_l$ [Losses in the lower arm]

$$P_0 = [P_U - L_U] + [P_L - L_L] \qquad (3)$$

The delay between the propagation of light in the upper and the lower arm Δt α width of the waveguide ω_L and ω_U .

E. Light path in MMI coupler

P_1

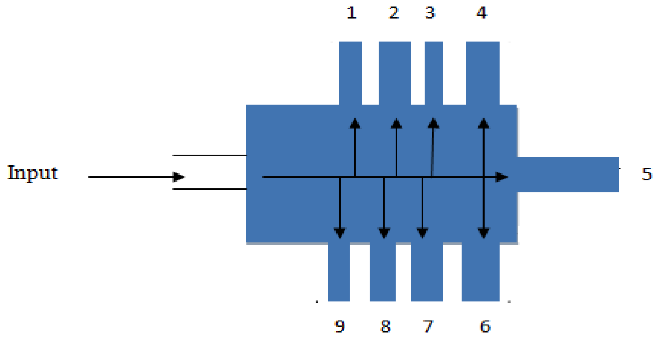


Figure 4: Light path in MMI coupler

From Fig.4

$\Delta t_1 \ \alpha \ \omega_L$

$\Delta t_2 \ \alpha \ \omega_U$

$$\Delta t_1 = \eta_{eff}\, \omega_L \qquad \Delta t_1 \ \alpha \ \Delta \phi_1 \qquad (4)$$

$$\Delta t_2 = \eta_{eff}\, \omega_U \qquad \Delta t_2 \ \alpha \ \Delta \phi_2 \qquad (5)$$

Due to the phase shift between the upper arm and the lower arm, there will be an interference pattern. There will be a maximum output when there is a constructive interference. However there is no destructive interference.

The phase difference between the two waves is $\Delta\phi = k\Delta x$ where k is the wave number

$$k = \frac{2\pi}{\lambda} \qquad (6)$$

and (Δx) is the path length difference between the two waves.
In the proposed device

$$\Delta x = \Delta x_i \qquad (7)$$

where Δx_i is the path length difference between the two adjacent ports

For 'n' outputs the path length difference is

$$\sum_{i=1}^{\eta} \Delta x_i = \sum_{i=1}^{\eta} l_i\, \eta_{eff} + \Delta\, \eta_{eff}\, \omega_i \qquad (8)$$

Where 'l_i' is the physical length ω_i is the width of each output waveguides.

$$\text{The phase difference } \phi i = \frac{2\pi}{\lambda} \sum_{i=1}^{\eta} \Delta x_i \qquad (9)$$

The insertion losses at the output ports

$$\text{Loss in dB at each output} = \left\{ 10 \log \frac{Pi}{Po} \right\} \qquad (10)$$

III. Principle Of Operation

1550nm TE polarised light is launched into a device through a taper device ensuring that maximum power is coupled to the fundamental mode. When the light enters to the MMI region the light diverges. There are different waveguides on either side of the MMI coupler and at the output. The width of all these waveguides is linearly varied. This results in the variation in the effective index. The optical path length difference measured from the MMI launching region to a different waveguides is varied. This results in the delay of the signal which ultimately results in phase shift. The measured delay depends on the position of the waveguide and the thickness of the waveguide which enables the device to be used as a delay line.

IV. Applications

This device can be used as True Time Delay Line for antenna beamforming,fast switching delay line in web camera Add/drop multiplexer and for health monitoring of civil structures.

V. Simulation Results

The laser light at 1550 nm is launched into a device through a taper waveguide and the polarization is optimized for TE mode.

A. The propagation of light in the proposed device is as shown in Fig.5.

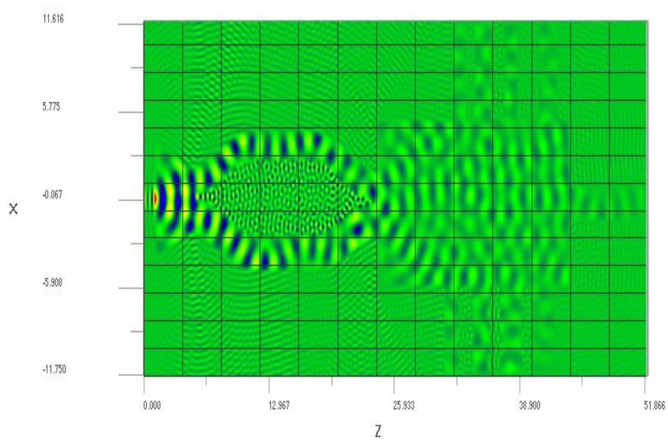


Figure 5: Propagation of light in the Nine bit Mach Zehnder Interferometer based Comb shaped Optical True Time Delay Line

B. The refractive index distribution of the proposed device is as shown in Fig.6.

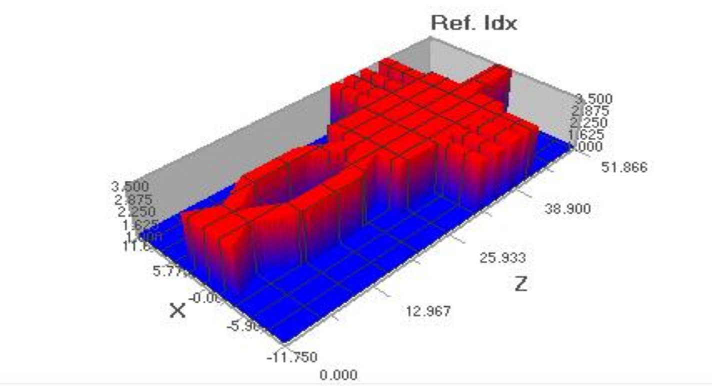
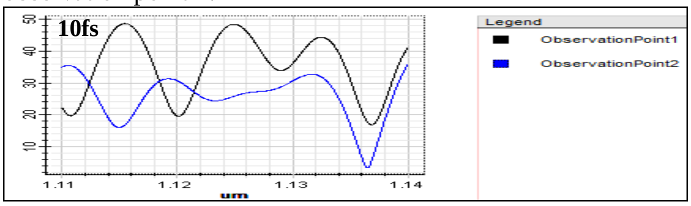


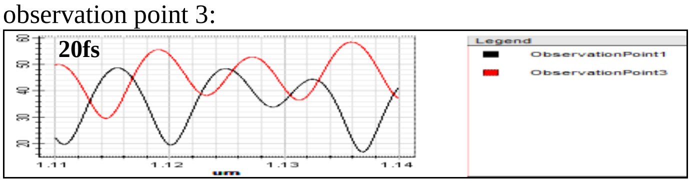
Figure 6: The refractive index distribution of the proposed device

C. Each graph in Fig. 7 shows the delay between reference waveform (at observation point 1) and waveform at each wavegide(from observation point 2 to observation point 10) and dealy in fs is as given on graph

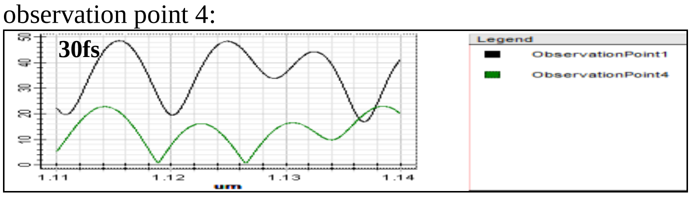
1.Graph shows the delay between observation point 1 and observation point 2:



2.Graph shows the delay between observation point 1 and observation point 3:

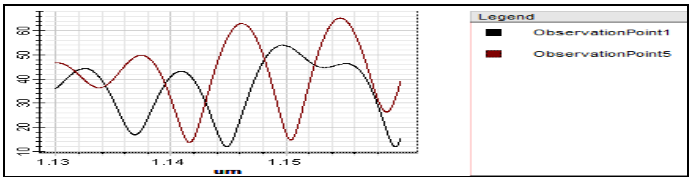


3.Graph shows the delay between observation point 1 and observation point 4:

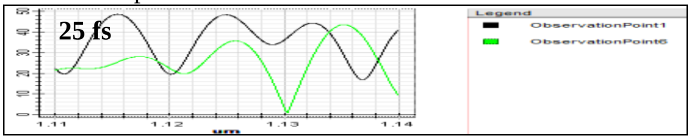


4.Graph shows the delay between observation point 1 and observation point 5:

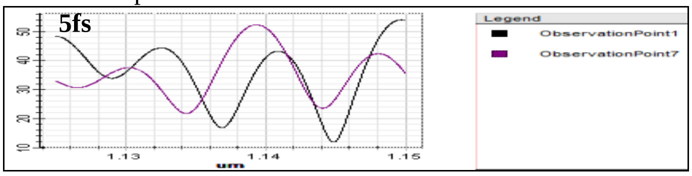
40fs



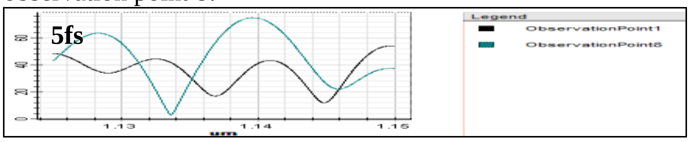
5.Graph shows the delay between observation point 1 and observation point 6:



6.Graph shows the delay between observation point 1 and observation point 7:



7.Graph shows the delay between observation point 1 and observation point 8:



8.Graph shows the delay between observation point 1 and observation point 9:

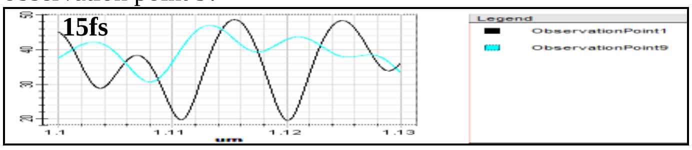
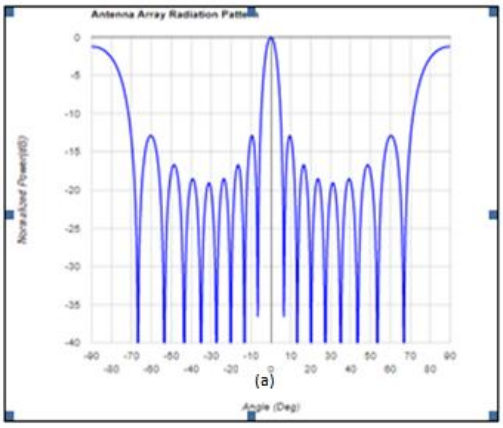
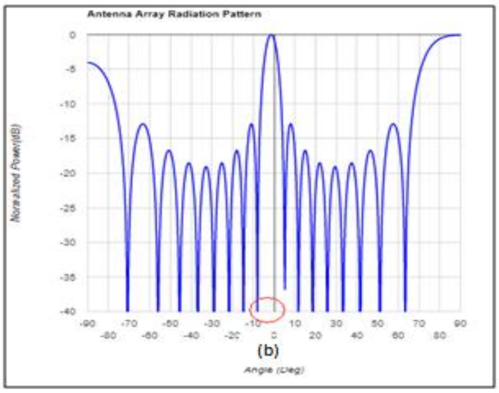


Figure 7 : Optical output waveforms at observation points of the linear waveguides from the device showing optical delays in fs as shown in above graphs from 1 to 8. The black lines are the reference signals passing through observation point 1 and different coloured lines represents various delayed signal line. The relative delay values are labelled on the graphs.

D. Radiation patters of antenna array at different delays out of all are given in the Fig. 8 :

	10	1	2	3	4	5	6	7	8	9
Delay	8 fs	125 fs	135 fs	145 Fs	155 fs	165 fs	150 fs	140 fs	130 fs	120 fs
Delay between Obs.point 1 and Obs.point 2 to 9	**1** 125 fs	**1-2** 10 fs	**1-3** 20 fs	**1-4** 30 Fs	**1-5** 40 fs	**1-6** 25 fs	**1-7** 15 fs	**1-8** 5 fs	**1-9** 5 fs	
Observati on point	**10**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Insertion loss in dB	**0**	**-26**	**-30**	**-24**	**-36**	**-24**	**-31**	**-27**	**-25**	**-25**





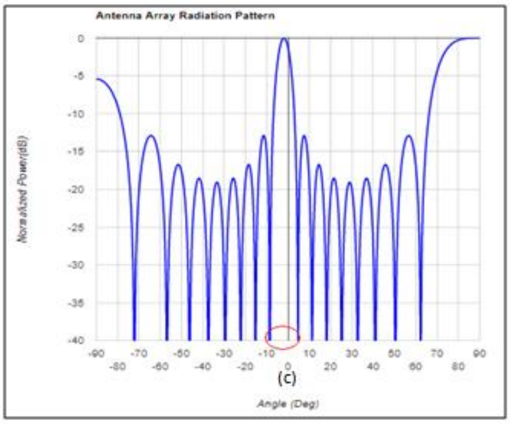


Figure 7 : Radiation patterns of antenna array at (a) no delay, (b) at observation point 1 the delay is 125fs and (c) at observation point 5 the delay is 165fs
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E. Summary of performance of the Nine bit Mach Zehnder Interferometer based Comb shaped Optical True Time Delay Line

Table 1: Summary of Nine bit MZI based comb shaped Optical TTD line

VI.Conclusion And Future Scope

A compact nine bit delay line is realised on Silicon platform achieving a maximum delay of 165µs.The variable delay obtained is fed to the antenna array.The radiation pattern varies with delay ensuring that microwave signal can be controlled by optical signal.The proposed device is compact as compared to the earlier seven bit delay line which provided 1.27ns and which spans in mm.By engineering the various parameters it is possible to convert this device as tunable delay line.

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