

Fully-integrated 4-bit True Time Delay Module using Polymer Optical Switches and Waveguide Delay Lines

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Abstract: A fully-integrated 4-bit true time delay module using polymer waveguide switches and delay lines is proposed. The module achieves small phase errors less than 0.75° , 120nm optical bandwidth and low power consumption of only 143mW.

OCIS codes: 250.5300; 250.5460; 130.3120

I. Introduction

Optical true time delay (TTD) modules using optical switches combined with optical delay lines [1] need no wavelength tuning, resulting in reduced system costs and enhanced resistance to harsh environments. Optical microelectromechanical system (MEMS) switches together with fiber delay lines [2] show desirable features such as low insertion loss and easy electronic control. However, the fibers have to be precisely cut in length in order to achieve accurate delays, and the couplings between fibers and MEMS switches remain to be a time consuming job. A more attractive approach is to integrate waveguide switches and delay lines on a single chip by planar lightwave circuit (PLC) technique [3]. The patterns defined by photolithography can deliver precise delays with subpicosecond resolution for the delay control of phased array antenna (PAA) systems. The fully-integrated photonic circuit eliminates the discrete couplings between delay lines and switches, therefore, it becomes more robust to harsh environments and occupies less space. Additionally, the fabrication cost can be much lower than the fiber-MEMS implementation. In this paper, a fully-integrated 4-bit polymer TTD module using thermo-optic switches based on the total internal reflection (TIR) effect is presented. Compared with other optical switch configurations such as Mach-Zehnder interferometers [4], directional couplers [5] or digital optical switches [6], TIR switches are not sensitive to the wavelength, thus providing the potential for wavelength division multiplexing (WDM), which can reduce the number of TTD modules in real systems. Additionally, TIR switches are much more compact with lengths of only several millimeters.

II. Design and Analysis

The configuration of the proposed TTD module is shown as Fig.1(a) which consists of input/output waveguides, five 2×2 TIR thermo-optic switches, four reference lines and four delay lines. Due to the fully-integrated approach, both optical switches and waveguide delay lines have a core index of 1.46 and a cladding index of 1.45. The $6.5\mu\text{m} \times 6.5\mu\text{m}$ cross section constrains the waveguide to be single mode and provides a good coupling efficiency with a single mode fiber. The TIR switches have a $250\mu\text{m}$ waveguide separation and 4° half branch angle, as Fig.1(b) shows. The waveguides are tapered from $6.5\mu\text{m}$ to $48\mu\text{m}$ in the junction area to reduce the switch cross talk and be compatible with the temperature distribution [7]. The switches are $4924\mu\text{m}$ in length including $500\mu\text{m}$ straight waveguide segments on each side to stabilize the optical mode into/out of the delay lines. The bend radii of the reference lines are 1.5mm, and those of the delay lines are 1.75mm. In order to reduce the bending loss and transition loss, waveguide offsets and trench structures are introduced. Micro-heaters are placed on the top cladding

layer and connected to bonding pads through lead lines. The proposed 4-bit TTD module can dynamically deliver a range of delays from 0 to 177ps in increment of 11.8ps.

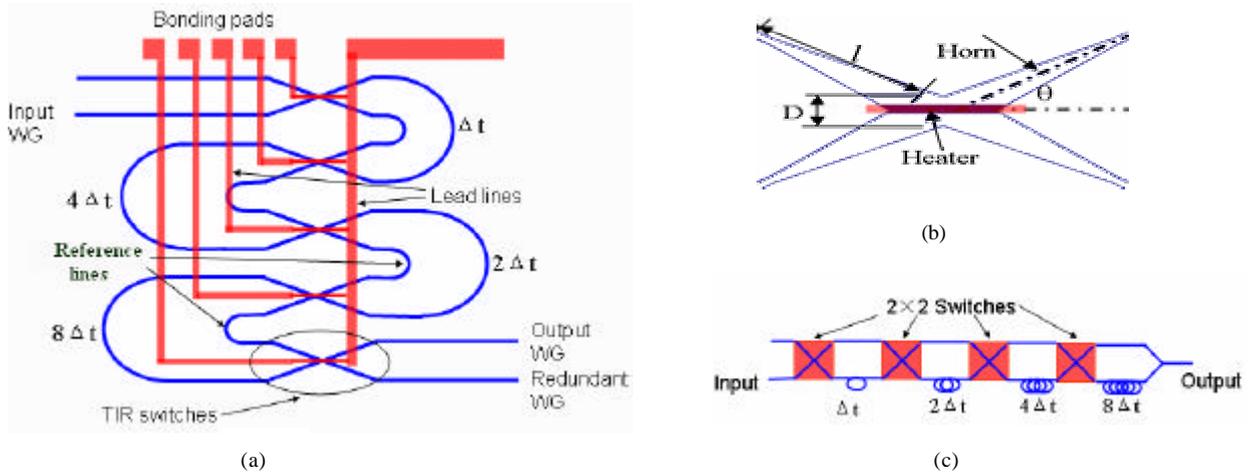


Fig.1 (a) Proposed 4-bit TTD device using TIR optical switches (b) Schematic of the TIR optical switches (c) 4-bit TTD schematic using four 2×2 optical switches and one 2-to-1 combiner

To route the optical signal to a single output waveguide, 0, 2 or 4 switches are required to be activated. Compared with the configuration in Fig.1(c), which is widely adopted in many TTD elements [3], the effect of the optical switch cross talk upon the radio frequency (RF) signal is significantly reduced. Detailed analysis will be given in the conference. Fig.2 shows the simulated results of the RF phase error due to the cross talk. The configuration of Fig.1(a) has a much smaller phase error than that of Fig.1(c). To overcome the volume relaxation induced cross talk aggravation, a large half branch angle of 4° is chosen since it can offer a dynamic cross talk below -30dB [6]. All possible RF phase errors due to the cross talk are simulated to be within $-0.15^\circ \sim 0.19^\circ$, which will be detailed in the conference.

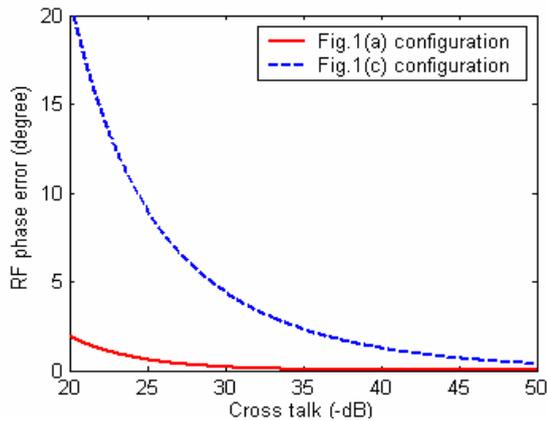


Fig.2 simulated RF phase errors caused by the cross talk

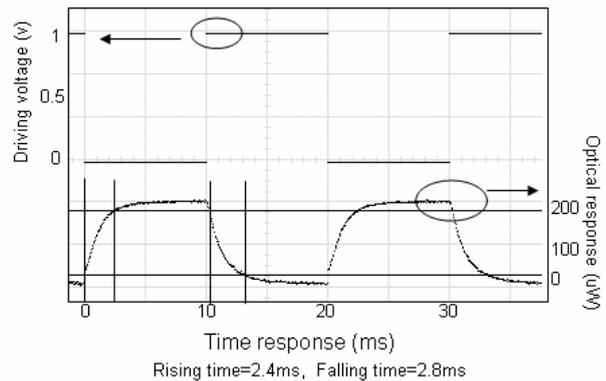


Fig.3 switching speed measurement of the 4-bit TTD device

III. Fabrication and Experimental Results

The UV Curable Fluorinated Acrylates, ZPU12-460 and ZPU12-450 from ChemOptics, are used to serve as the core and cladding materials. They are spin coated and etched by reactive ion etching (RIE) to form the waveguide structure. The micro heaters and lead lines, including bonding pads, are patterned by a lift-off process to get a

uniform line width. In the third layer, the trenches and lead line windows are opened by photolithography, followed by lead lines electroplating to reduce the resistance. Another RIE step is performed to form the trenches to reduce the bending loss. In the back-end process, the TTD waveguide module is diced and polished to get good coupling facets with single mode fibers. The five discrete wire pads and one common ground pad are wire bonded to a PCB. The fabricated TTD module has a compact size of 21.7mm×13.7mm.

The measured RF phase errors are between -0.75° to 0.62° . The power consumption of the fabricated module depends on the working state. The maximum value is 143mW with 4 switches fully activated, which is only 1/10 of the DOS switches in [8]. The total fiber to fiber insertion losses vary from 13.2 to 16.6dB for different delay configurations, due to the waveguide propagation loss and the output non-uniformity of the switches in the cross and bar states. The integrated module shows a uniform output response to the tunable wavelength from 1480~1600nm and the cross talk is below -25dB. The switching speeds of the TIR switches are measured by applying a 50Hz square wave signal with a 50% duty cycle. Both the on and off state switching time are measured to be less than 3ms, as shown in Fig3.

IV. Summary

The fully-integrated 4-bit TTD module using TIR switches exhibits accurate delays, low power consumption, wavelength insensitivity, small chip size and low fabrication costs. The insertion loss at the wavelength of 1550nm is 13.2 to 16.6dB, depending on the delay paths and the states of optical switches. The switching time of the TIR switches is below 3ms. The simulations predict that the cross talk induced RF phase errors are negligible, which are confirmed by the experimental results.

Acknowledgements

This work was supported by Contract N00039-03-C-0057; Linda L. Whittington, SPAWAR/PEO C4I & Space, SBIR Program Manager.

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