applied optics

Scalable and reconfigurable true time delay line based on an ultra-low-loss silica waveguide

Qian Qian Song, Zhe Feng Hu, and Kai Xin Chen*

School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
*Corresponding author: chenkx@uestc.edu.cn

Received 19 March 2018; revised 26 April 2018; accepted 27 April 2018; posted 30 April 2018 (Doc. ID 326377); published 24 May 2018

A scalable and reconfigurable on-chip optical true time delay line consisting of Mach–Zehnder interferometer (MZI) switches and delay waveguides is proposed and demonstrated with the ultra-low-loss silica waveguide platform. The MZI switches provide the reconfiguration of the light traveling paths and hence different delays. Our proposed structure can be easily scaled to an M bit delay line with a slight increase in dimensions. The footprint of our fabricated 1 bit delay line is 33 mm × 13 mm (length × width) and can provide a delay of 6.0 ps with an insertion loss of 1.2 dB at the operating wavelength of 1550 nm, while the footprint of the 4 bit delay line is 43 mm × 14 mm and can provide a discrete delay tuning from 6.0 to 90.2 ps with a delay deviation lower than 0.2 ps and a tuning response time of 0.84 ms. The insertion losses are lower than ∼2.34 dB, and the extinction ratios are greater than 20.42 dB. The average switching power is ∼132.6 mW. Our proposed optical true time delay lines could find applications for optical beamforming in phased array antennas.

OCIS codes: (130.3120) Integrated optics devices; (130.4815) Optical switching devices; (160.6030) Silica.

https://doi.org/10.1364/AO.57.004434

1. INTRODUCTION

Optical delay lines play an important role in the implementation of optical signal buffering and optical packet synchronization in communications and information processing [1–3] as well as the achievement of real-time imaging in optical coherence tomography [4]. In addition, they are also key components for microwave photonic filters and optical beamformers in microwave photonics (MWP) fields [5–9]. Among these applications, it is attractive and promising to use optical true time delay lines for optical beamforming in phased array antennas (PAA) because they can increase the bandwidth of the antenna and avoid beam squinting and electromagnetic interference [6]. For a practical PAA system, true time delay lines, which can achieve configurability and scalability, are especially desired to provide the flexibility of the system [6,7].

Optical delay lines can be realized based on optical fibers and optical waveguide technology. However, in contrast with fiber delay lines, optical waveguide delay lines, fabricated by the photolithographic methods for various waveguide materials, are able to achieve precise delays with sub-picosecond order of resolution, broader radio frequency (RF) bandwidth, and more compact size for PAA systems [7]. More importantly, with optical waveguides, on-chip tunable optical delay lines can be easily realized by introducing a resonant mechanism [8–16] or by integrating optical waveguide switches [16–22] into the circuits, in which the former can realize continuous tuning, while the latter can achieve discrete tuning or reconfiguration.

Resonant mechanisms, including material resonance [8] and circuit resonance [9–16], can be used to change the group velocity so as to realize delay. Delay lines based on a circuit resonance mechanism usually exploit microring configurations and can provide continuously tunable group delay up to the order of nanoseconds with compact devices [11], but the expense is a large loss and narrow bandwidth [23]. Coupled microring resonators can increase the bandwidth, but they commonly require complex tuning strategies [12]. Graphene monolayer electrodes, together with microring resonators or Bragg grating structures, can enable reconfigurable operations and increase the maximum delay time and bandwidth of optical delay lines, but they have not been proved in experiments and also require complex tuning strategies [14–16]. Another important way to realize an optical tunable delay line is to exploit a reconfigurable structure consisting of a set of optical paths in different physical lengths connected by a series of switches. Although the achieved tunable time delay is discrete, this method offers larger bandwidth and finer control of tuning, which are important properties for the application of optical beamforming in PAA systems. Besides the aforementioned two main methods, a continuous delay tuning has been demonstrated based on a Mach–Zehnder interferometer (MZI) with tunable couplers [24], while a discrete delay tuning has also been demonstrated based on a spectrally cyclic-arrayed waveguide grating feedback loop [25], or based on two semiconductor optical amplifier Mach–Zehnder interferometer wavelength converters and on-chip packet delay [26].

Integrated reconfigurable true time delay lines based on different architectures have been proposed with different waveguide platforms, including SiON [10], Si [11,12,17,26], polymer [18,19], Si_3N_4 [9,20–22], and InP [24,25]. Among them, the polymer platform has a higher propagation loss and is sensitive to ambient temperature and humidity; however, due to their quite small waveguide dimensions, the other platforms have a higher coupling loss even if a specially designed taper or grating is used to increase coupling efficiency. Therefore, the devices based on these platforms have a potential drawback for RF signal processing due to its high optical insertion loss. A linear increase in optical loss will cause a quadratic increase in the loss of the RF signal [23]. Compared with the devices above, the ones based on the silica platform have the advantage of low propagation and coupling losses. The propagation loss of 0.03 dB/cm and coupling loss of 0.4 dB per joint on a silica waveguide platform have been demonstrated [27,28]. In [13], the delay line with an insertion loss of 0.9 dB has been demonstrated with silica waveguides of 2% index contrast. Moreover, silica-based waveguide devices, e.g., arrayed waveguide gratings (AWG) and optical splitters, have been successfully developed and put into operation. Table 1 summarizes the configurations and the performance of the aforementioned experimental integrated optical delay lines.

In this paper, we propose and demonstrate a scalable and reconfigurable on-chip optical true time delay line with the ultra-low-loss silica waveguide platform. Our proposed delay line architecture consists of a set of optical waveguides in different physical lengths connected by MZI switches. The MZI switches provide the reconfiguration of the light traveling paths and hence different delays. The most outstanding advantage of the proposed structure is that it can be easily scaled to an M bit delay line with a slight increase in dimensions. The scalability of the proposed delay line is decided by the delay increment and the refractive index contrast of the waveguide materials used. The footprint of the fabricated 1 bit delay line is 33 mm × 13 mm (length × width) and can provide a delay of 6.0 ps, while the footprint of a 4 bit delay line is 43 mm × 14 mm and can provide a discrete delay tuning from 6.0 ps to 90.2 ps with a delay deviation lower than 0.2 ps and a tuning response time of 0.84 ms. Thanks to the ultra-low-loss silica waveguide platform, the fabricated 4 bit delay line shows insertion losses lower than ~2.34 dB and extinction ratios greater than 20.42 dB. The average switching power is ~132.6 mW. The proposed optical true time delay lines could find applications for optical beamforming in phased array antennas.

2. CONFIGURATION AND DESIGN

The topological structure of the proposed reconfigurable optical waveguide delay line is shown in Fig. 1 (a). The device includes delay units and switch units. Each delay unit consists of two single-mode waveguides in different physical lengths.

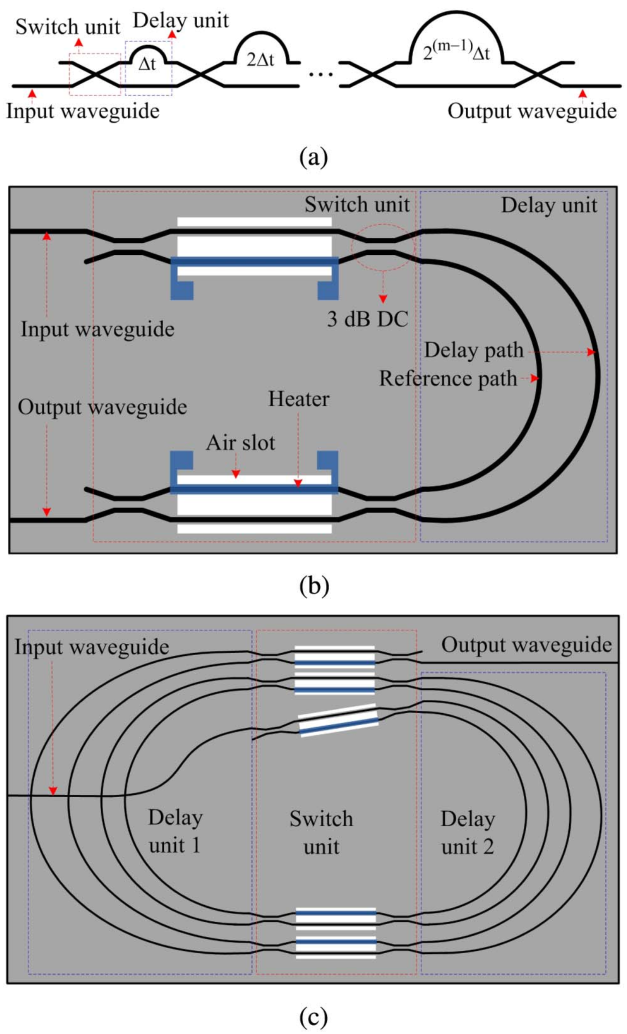

Fig. 1. Diagram of the proposed reconfigurable optical waveguide delay line. (a) Topological structure of the proposed delay line. (b) 1 bit waveguide delay line. (c) 4 bit waveguide delay line.

Table 1. Configurations and the Performance of the Aforementioned Experimental Integrated Optical Delay Lines

Configurations	Insertion Loss (dB)	Delay/Increment(ps)	Power (mW)	Area (mm^2)	ER (dB)	Ref.
PhC	<10	70	NA	~mm	NA	[8]
MZI+Ring-Si	12.4	1280	<13.5	28.62	>25	[11]
SCISSOR-Si	14	135/1.6	~30	NA	NA	[12]
MZI-Si	16	1270/10	105	11.84	13	[17]
TIR-Polymer	14.9	177/11.8	44	297.27	NA	[18]
X-Junction-Polymer	18.34	182.9/60.9	NA	144	NA	[19]
MZI-Si_3N_4	14	12350/850	260	3825	19.3	[20]
MZI-InP	NA	15	76.2 mA	NA	NA	[24]
AWG-InP	6.5	71.6	NA	NA	25	[25]
SOA-Si	NA	17200/6500	5880	13.2	6.2	[26]