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Optics Letters

Integrated remotely tunable optical delay line for millimeter-wave beam steering fabricated in an InP generic foundry

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A compact and fabrication-tolerant integrated remotely tunable optical delay line is proposed for millimeter-wave beam steering and is fabricated in an InP generic foundry. The proposed delay line is based on a spectrally cyclic-arrayed waveguide grating feedback loop. Its major features include the tolerant architecture with reduced chip size, and bi-directional operation with simplified remote tuning. Moreover, its cyclic feature guarantees further cascaded operations either for 2D radio beam steering or for high-resolution delay generation. The experimental results show less than 6.5-dB insertion loss of the integrated delay line. Five different delays from 0 to 71.6 ps are generated with less than 0.67-ps delay errors. © 2015 Optical Society of America

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The current explosion of communication traffic volume is driven by an insatiable appetite for high-speed internet connectivity and video-based content delivery to wireless and mobile terminal users, especially for in-home scenarios. A lot of research has been carried out to expand wireless capacity via spatial techniques. Unlike spatial multiplexing, which requires complicated digital signal processing, radio beam steering (BS), which is sometimes referred to as spatial filtering, directs signals to the desired users with minimum interference. Optical true-time delay is widely used for broadband radio-beam steering to avoid the beam squint problems [1–7]. Recently, radio-over-fiber systems incorporating optical true-time-delay radio-beam steering have been proposed for in-home networks [3,4]. However, current optical tunable delay lines (OTDLs) based on bulk-optics components limit their further applications [8,9]. An integrated OTDL with remote control can reduce the complexity of radio access points, which matches the centralization nature of beam-steered RoF systems. Historically, there are mainly two approaches to realize the integrated OTDLs. The first is based on physical length-induced delay [1,10,11], and the second is based on optical filtering-induced

group delay [12–16]. As a representative example of the first kind, an optical radio-beam steering chip with wavelength (de-)multiplexer, discrete delay lines, and Mach–Zehnder interferometer (MZI) switch was proposed by Soares *et al.* in [10]. In this chip, an arrayed waveguide grating (AWG) is used as a (de-)multiplexer for wavelength separation. Delays for different antennas are generated on a wavelength basis, and the delays are step-wise tuned by a 3-stage MZI-switch. In general, the first kind of integrated OTDLs can provide broadband but step-wise tunable delays. The angular resolution of a radio beam then depends on the step number. The second one can provide continuous tuning of group delay based on all-pass filters. Madsen and co-workers explored the possibility to use optical ring resonators (ORRs) as all-pass filters [15,16], and an elegant theoretical analysis framework based on digital filter concept was proposed and developed [17]. Later, Zhuang *et al.* demonstrated a prototype of integrated OTDLs of multiple ORRs [12]. However, such an approach suffers the narrow operation bandwidth limited by the inherent feature of filter resonance. Cascaded ORRs can overcome such limitation to some extent but at the expense of large chip area and complicated trimming [18]. In a word, the first kind of integrated OTDLs are suitable for broadband applications with low angular resolution, while the second one matches the narrowband applications desiring relatively higher angular resolutions. In-home communication is usually with very high throughput and limited space (thus results in low angular resolution), which makes the first kind of integrated OTDL suitable for such applications. Arrayed waveguide-grating feedback loop (AWG-loop) is a good option [19]. To allow two-dimensional (2D) squint-free radio-beam steering by means of single-parameter tuning, we proposed the concept of spectral-cyclic AWG-loop (SC-AWG-loop) for 2D radio beam steering. In this Letter, we realize and demonstrate an integrated spectral-cyclic arrayed waveguide-grating feedback loop (SC-AWG-loop) through the generic-foundry-based InP platform from PARADIGM project. The photonic integrated circuit (PIC) was fabricated with its successful yielding in the first run. The insertion loss (IL) of our PIC including the two travels through the SC-AWG is less than 6.5 dB with 1.8-dB flatness, which allows operations with high dynamic range.

Fig. 1. Principle of proposed AWG-loop-based integrated optical tunable delay line (OTDL). (a) the AWG-loop; (b) 1-by-2 optical delay network; (c) the spectral transmission of an N-by-N cyclic AWG; (d) and (e) the delay at Out-2/-1 of (b). OS, optical splitter.

The integrated SC-AWG-loop is schematically shown in Fig. 1(a). A fiber system using a discrete AWG component and fiber delay lines has been demonstrated [1] for 10–40-MHz operation. Due to its bulk size, such a system can only work properly for large delays (and results in low operational frequency) with low delay accuracy. There are two main advantages of the proposed integrated SC-AWG-loop. The first is that the AWG is designed to be spectral-cyclic, which allows the interleaved operation as discussed in [20]. The second is that the integrated SC-AWG-loop with small footprint enables short delays with high accuracy, which suits high-frequency operation like at mm-wave bands. As shown in Fig. 1(a), the N-by-N SC-AWG functions both as a wavelength multiplexer (MUX) and de-multiplexer (de-MUX). Its spectral transmission is schematically shown in Fig. 1(b). The feedback loops (optical waveguides) connect N-1 pairs of inputs and outputs in a symmetric configuration for recirculating operations and leave one pair for the external input and output. This SC-AWG-loop is topologically equivalent to two AWGs in series with a delay element in between, which works as a step-wise OTDL. As shown in Fig. 1(c), an optical signal through the SC-AWG-loop can be stepwisely tuned with its wavelength tuning. The delay number and resolution depend on the number of AWG inputs and outputs, which can be made as large as a thousand. There are some advanced features of the proposed SC-AWG-loop. First, by reusing the same AWG as MUX and de-MUX, its footprint can be significantly reduced (approximately by half). Moreover, its fabrication tolerance is enhanced since the spectral misalignment does not exist for the identical MUX and de-MUX. Third, it can support delay tuning with remote wavelength tuning, which enables a centralized and simple network. Finally, it can simultaneously support bi-directional operations. As shown in Fig. 1(a), the solid and dash arrows denote left-to-right and the opposite operations, respectively. Such operations are highly demanded for telecom systems including up- and down-links. By reusing one device, the footprint and stability can benefit.

The integrated circuit is fabricated on a 3-in. InP wafer with 500 μm thickness (which is thinned down to 250 μm after processing). There are two types of waveguide cross-sections employed in our design: a low-index-contrast waveguide cross-section E200 (200 nm etch) and a high-index-contrast

one E1700 (1700 nm etch). E200 is with low-loss for AWG free-propagation regions (FPRs), while E1700 with small radius is for waveguide connections. A generic foundry approach for the device design and fabrication is employed inside the framework of PARADIGM project [21]. Comparing with discrete component [22,23] and photonics crystal [24], such designs can be fully integrated [25].

The core component for the SC-AWG-loop is a cyclic 5-by-5 AWG. The mask layout and photo of the test structure of the AWG are shown in Fig. 2(a). The spectrum centre of the AWG (λ_c) is designed at 1550 nm, and the grating order is designed to be 174. Its free spectral range (FSR) is 8 nm (1000 GHz) with 1.6-nm (200-GHz) channel spacing (CS). Five spot-size converters (SSCs) are used to allow better lateral fiber coupling. The measurement setup of the AWG is shown in Fig. 2(b). 16.9-dBm amplified spontaneous emission (ASE) noise from an EDFA is launched into a polarization beam splitter to allow the pure TE or TM polarization of the ASE noise. The cleaved single-mode fiber (CF) is employed for lateral optical coupling. A polarization controller (PC) is employed to adjust the polarization of the injected optical signal aligned with the TE mode of the input SSC [In-0 marked in Fig. 2(a)]. The waveguide connecting In-0 is located at the middle of the input FPR. The other cleaved fiber is used to collect the optical signal from the outputs (Out-0–Out-4) shown in Fig. 2(a). An optical spectrum analyzer (OSA) with a resolution of 0.02 nm is used to record the measured results. The coupling loss of the SSCs is 1.75 dB per facet. The waveguide loss of E1700 is 1.25 dB/cm for TE mode. The measured spectral transmission of the AWG is shown in Fig. 2(c). The optical link including the polarization controller introduces around 2-dB loss. The ASE noise is first launched into a waveguide test structure and is then recorded by the OSA as a reference for further calibration. The Out-2 waveguide of the AWG test structure is damaged, which results in the missing of the transmission of Out-2 in Fig. 2(c). The measured spectral center of Out-2 (measured λ_c) is at 1546.8 nm. The IL of the AWG is better than 2.8 dB, and the IL difference of all channels is less than 0.9 dB. The crosstalk is measured better than 25 dB. An FFT operation of the measured spectral transmission data is performed, which indicates the 8-nm FSR and the 1.6-nm CS. The 0.52 nm -3 dB pass-bands are obtained for all channels,

Fig. 2. (a) The mask layout and photo of the AWG test structure, (b) the measurement setup, and (c) the measured spectral transmission of the AWG.

which means 65-GHz electrical bandwidth for radio signals. The cyclic-spectral feature is clearly observed in Fig. 2(c).

The measurement setup of the SC-AWG-loop is shown in Fig. 3(a). The 12.9-dBm optical carrier from a tunable laser passes to a Mach-Zehnder modulator (MZM) via a PC. An electrical pulse with 500-ps duration generated from an electrical arbitrary waveform generator (E-AWG) is amplified by a 12-GHz electrical amplifier with a 19-dB gain (SHF100APP) to drive the MZM. The modulated optical signal with 2.6-dBm power is then launched to the input of the SC-AWG-loop (In-0) via a cleaved fiber. A PC is used to align the polarization to the TE mode of waveguides in the SC-AWG-loop. Another cleaved fiber is employed to collect

the output optical signal. With an EDFA [OA shown in Fig. 3(a)], the collected optical signal is amplified to 5.1 dBm before illuminating a 40-GHz photodiode (u2t). The detected electrical signal is then amplified by an EA (SHF100APP) and is further sampled by a digital phosphor oscilloscope (Tektronix DPO70000) with an equivalent-time sampling mode. The oscilloscope is locked to the E-AWG by a 10-MHz reference clock. The sampling rate is 2.5 TSaps, and thus the time resolution is 400 fs. The sampled signal is then offline processed to obtain the delays based on the time-domain correlation method. The photo of the SC-AWG-loop under test is shown as an inset of Fig. 3(b). A 5-by-5 cyclic AWG identical to a previously measured one is used in the SC-AWG-loop. The waveguides connect four pairs of input and output to form the feedback loops with different delays. One pair of input and output of the AWG (In-0, Out-0) is used as the input and output of the SC-AWG-loop and is connected to two SSCs. The maximum delay (Path-4) is designed to be 12.5 ps for π phase shift at 40 GHz. The designed delays of Path-1 to Path-4 are progressively increased from 0 to 12.5 ps.

The loss of one open path (Path-0) and four feedback loop paths (Path-1 to -4) is measured as shown in Fig. 3(b). The 3.5-dB coupling loss (1.75 dB per facet) and 2-dB link loss are taken into account. The tunable laser (TL) is employed to provide fine-tuning of the wavelength for the transmission peak searching. For the loss measurement, the MZM and OA are bypassed, and the OSA is replaced by an optical power meter. The measured results show that the loss for all channels is less than 11.9 dB. Subtracting 5.5 dB off-chip loss, the measured results show 6.4-dB loss, which is comprised of twice the AWG IL and the loss of waveguides in between. Such IL is acceptable for many microwave photonics applications. Considering the 1-dB waveguide loss, and the 2.8-dB IL measured from the AWG test structure, the measured IL of the SC-AWG-loop exhibits a high consistency with its test structure counterpart. For Path-0, since it travels the AWG only once, its IL is less 8.8 dB. A 3.1-dB averaged loss reduction is observed for Path-0 compared with the others. Path-1 to Path-4 exhibit higher loss because of an extra AWG travel. Due to the

Fig. 3. Measurement of the proposed AWG-loop, (a) the measurement setup; (b) time domain correlation for delay measurement.

Fig. 4. Measured delays of different delay channels of the AWG-loop.

cyclic feature of the AWG, the loss also exhibits the cyclic feature. The loss variation of Path-0 is less than 0.5 dB, while the ones of Path-1 to Path-4 are less than 1.8 dB. The measured λ_c is 1547.4 nm (Path-1), suggesting a 0.6-nm spectral offset from the AWG test structure. However, such spectral offset does not induce any misalignment, because the MUX and de-MUX are the same one in the feedback loop configuration.

The sampled signal traveling from Path-0 is used as a reference signal for delay measurement. The cross-correlation is performed between the reference signal and the others. Path-0 can be found based on the minimum loss as indicated in Fig. 3(b). For the wavelengths directly traveling from In-0 to Out-0 (Path-0), the total delay is equal to the cross delay of the AWG (AWG-delay). For other wavelengths going through the feedback loops, the total delay includes twice the AWG-delay plus the delay of the feedback loops (loop-delay). Thus, we can see the four progressive delays and also one “fall-down” delay (Path-0) shown in Fig. 4. As shown in Fig. 4, the linear delays are exhibited for Path-1 to Path-4 with 12-ps delay, which is a little smaller than the delay (12.5 ps) we designed. This could be induced by the limited time resolution (400 fs) of the DPO. The detailed delay values are also indicated in the inset table of Fig. 4. The differences between the designed delays and the measured ones for Path-1 to Path-4 are -0.5, 0.1, -0.76, and 0 ps from 1540 to 1548 nm. And the delays of the same paths but at different wavelengths from Path-1 to Path-4 are 0.2, -1, 0, and 0.2 ps. The acceptable matches between the designed delays and measured ones demonstrate the high design accuracy.

To conclude this Letter, we propose an integrated broadband optical tunable delay line based on the cyclic AWG feedback loop for mm-wave beam steering. The experimental results show less than 6.5-dB IL of the integrated SC-AWG-loop. Five different delays from 0 to 71.6 ps are generated with less than 0.67-ps delay errors.

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