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Integrated Wavelength-Tuned Optical mm-Wave Beamformer With Doubled Delay Resolution

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Abstract—Integrated optical true time delay lines attract lots of attention for optically controlled mm-wave beam steering due to its low-loss/broadband performance and stable/compact system architecture. However, for remotely-controlled networks, the techniques that require local-site actively-tuned elements would make the network control more complicated. A passive design using wavelength-tuning is regarded as a promising candidate. In this paper, an integrated wavelength-tuned optical mm-wave beamformer with doubled delay resolution is proposed and demonstrated in a generic InP platform. A bidirectional looped-back arrayed waveguide grating (AWG) module acts as the stepwise tunable delay unit. By introducing an extra AWG router for delay mode (positive/negative) selection and a bidirectional optical interface, a pure λ -tuned, resolution-doubled optical delay network is realized without using any active component (e.g. heaters, current injection) at the local site. This photonic passive design is more beneficial to the remotely-controlled mm-wave beam steering system. Furthermore, the AWG router potentially allows multi-port wavelength switching to support the scaling-up of the network. The fabrication-caused delay error of <1.1 ps is experimentally verified on-chip. A further proof-of-concept 38-GHz fiber-wireless beam steering system with a 186° angular steering is experimentally demonstrated using QAM-4 modulation. Accurate mm-wave phase shifts originated from the proposed optical beamformer are obtained, which proves the effectiveness of the tunable integrated beamformer.

Index Terms—Indoor fiber-wireless communications, integrated photonics, looped-back AWG, optical mm-wave beamformer, wavelength-tuned.

I. INTRODUCTION

WIRELESS traffic is getting congested because of the relentlessly growing demand for broadband mobile services [1]–[3]. Thus as a key technology in 5G mobile wireless communication systems, millimetre-wave (mm-wave) communication offering high bandwidth attracts lots of attention to

address the imminent wireless traffic crunch [4], [5]. Especially, the mm-wave beam-forming/-steering boosts capacity by employing spatial channel multiplexing [6]. However, the required low-loss and broadband true-time delay at mm-waves are hard to be realized in the CMOS platform limited by the technology characteristics. Optical true-time delay (OTTD) with inherent low loss and broad bandwidth is used to solve this problem both on integrated circuit-level [7]–[10] and system-level [12]–[14]. Compared to the bulk-optics components based optical true time delay lines (OTDLs), integrated OTDLs are more attractive because of their stable performance and compact system integration [9]. Currently, many methods based on integrated optics are investigated such as the ring resonator-based tunable OTDL [10], [15] and the OTDLs based on optical switches [7], [16]. However, these techniques require active tuning elements in the remote site to steer the mm-wave beam, which complicates the centralized and remotely-tuned architecture as shown in Fig. 1, and even reduce the improvement of system stability. In our previous work [8], [9], [11], remotely λ -tuned optical delay networks (ODNs) have been proposed, designed and characterized. The integrated OTDL was implemented by a looped-back arrayed waveguide grating (AWG), which is a broadband, reliable, and low-cost scheme. This design has no active components at the local site (such as a transmitter) but true-time-delay by means of wavelength. Compared to thermal-optics-based continuously-tuned designs [10], [15], [17], [18], the λ -tuned ODN enables a more flexible access network. While how to increase the delay resolution and thus how to increase the number of steered spatial channels is still a problem. Here, the delay resolution is the number of available discrete time delays. As described in [11], the delay resolution is determined by the number of feedback loops inside an AWG. Hence, once the looped-back AWG is fabricated completely, the available physical stepwise time delays cannot be changed anymore. Therefore, the concept of the bidirectional ODN (Bi-ODN) is proposed to further increase delay resolution, which is shown in our previous work [19]. However, the design in [19] only shows the initial concept and could not achieve completely passive-based remotely-controlled bidirectional mm-wave beam-steering as shown in Fig. 1.

In this paper, we propose an entirely wavelength-controlled integrated Bi-ODN for mm-wave beam steering by utilizing a specially designed bidirectional optical interface, a looped-back AWG delay line, and an AWG router. By including a positive delay in addition to its negative counterpart, the delay resolution

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Fig. 1. Remotely λ -controlled optical mm-wave beam steering.

is doubled. Thanks to the AWG router, the passive single-input Bi-ODN is built, which potentially supports multi-port wavelength switching of a scaled-up network. The rest of this paper is arranged as follows: Section II describes the operational principle of the wavelength-tuned Bi-ODN for mm-wave beam steering; Section III gives the chip design and measurement; Section IV defines the proof-of-concept 38-GHz fiber-wireless beam steering system to show the effectiveness of the tunable integrated beamformer; Section V shows the experimental results and discusses these; and finally, Section VI gives the paper conclusions.

II. OPERATIONAL PRINCIPLES

The principle of the wavelength-tuned Bi-ODN for mm-wave beam steering is schematically shown in Fig. 2. Fig. 2(a) describes a looped-back AWG with four feedback waveguide paths where the AWG acts as both a wavelength multiplexer and demultiplexer by connecting inputs and outputs. This architecture is topologically equivalent to two AWGs in series and thus it is an almost half-sized and fabrication-tolerant design [11]. Here, a pair of input/output waveguides is selected as the bidirectional in-port and out-port. Its delay is t_0 with respect to the wavelength of λ_0 . The feedback paths are set in increments of Δt . The delay response versus the spectrum of the looped-back AWG is also shown (measured delay at out port) on the right part. Due to the AWG's spectrally cyclic characteristic, the delay response is also cyclic. In one free spectrum region (FSR), each wavelength (λ_0 to λ_4) is split into a different feedback loop and experiences a different delay (from t'_0 to $t'_0 + 3\Delta t$). However, the inherent large delay ($t'_0 - t_0$) between through-path and looped-back paths causes the spatially-discontinuous beam steering. Thus, in a practical ODN, the specially designed optical interface based on offset delay lines is necessary before each output port. Fig. 2(b) presents the regular ODN, where the delay of each output successively increases. This is a 1-by-4 network and each output introduces an individual offset delay line. The right part of Fig. 2(b) describes the delay response of a 1-by-2 ODN. The

Fig. 2. (a) The schematic configuration of the proposed λ -switched Bi-ODN for mm-wave beam steering; (b) the regular ODN; (c) the λ -switched Bi-ODN. Bi-ODN: bidirectional optical delay network.

offset delay of Out-1 can be set between t_0 and $t'_0 + 3\Delta t$. In order to realize both positive and negative delays between two outputs, one possible delay offset is set as $t'_0 + 1.5\Delta t$ and the relative delays are $0.5\Delta t$, $-0.5\Delta t$, $1.5\Delta t$ and $-1.5\Delta t$, respectively. The delay resolution is 4. In contrast, our resolution-doubled Bi-ODN is shown in Fig. 2(c). A specially designed passive bidirectional optical interface, which contains a bidirectional hybrid coupler (BHC) and an offset delay subsystem, is introduced for bidirectional operation. The delay resolution grows from N ($N = 4$) to $2N$ by extending the negative delays. Here N is the number of delays in a looped-back AWG. The AWG router

Fig. 3. (a) The mask layout of the λ -switched Bi-ODN; (b) The measuring system of the structure on chip; (c) The measured amplitude response of two optical outputs. SSG: spot size converter; wg: waveguide; MMI: multimode interferometer; PBS: polarization beam splitter; PC: polarization controller; CF-in: the input cleaved fiber; LF-out: the output lensed fiber.

switches the input signal to different output waveguides with respect to the wavelength. And each output channel spectrally covers at least an FSR of the looped-back AWG (>32 nm). Then the wavelengths are split into two groups I) λ_1 to λ_4 for channel-I; II) λ_6 to λ_9 for channel-II. Therefore, the Bi-ODN not only doubles the resolution via the same looped-back AWG but also supports completely wavelength tuning. This means, at the local side, no active tuning element is required and thus there is no controlling information delivery, which allows a more reliable and flexible network.

III. CHIP MEASUREMENT RESULTS

Fig. 3(a) shows the mask layout of the 1-by-2 Bi-ODN. One spot-size converter (SSC) on-chip is used to optimize the lateral

fiber-to-chip coupling. The coupled light is firstly λ -switched to Path-1 or Path-2 via an AWG router. Then it is split into two paths by a BHC (as shown in Fig. 3), which contains two 2-by-2 multimode interferometers (MMIs) and two offset delay waveguides [19]. One path is for electrical Out-1 (or optical Out-1) through the offset delay waveguide. The other branch is guided into the looped-back AWG followed by another BHC. The parameters of this AWG are as follows: 8-nm FSR with 1.6-nm channel spacing [11]. It should be pointed out that the optical outputs will be removed in practical applications. Thus the measured optical loss will be reduced by 3 dB as well. Two electrical outputs are used to convert the optical signal to mm-wave signals. The individual optical waveguide ('wg' in Fig. 3(a)) is used for power normalization. The intensity response is measured using the setup shown in Fig. 3(b) and the results' analysis is depicted in Fig. 3(c). In this section, optical power loss respecting to the wavelength at two output waveguide ends are measured. First of all, a 5-dBm optical source is amplified to 13 dBm by using an erbium-doped fiber amplifier (EDFA) and then is fed into a polarization beam splitter (PBS). Here, the PBS acts as a polarization state filter to eliminate unwanted signals. Furthermore, a fiber polarization controller (PC) is utilized to optimize the optical fiber-to-grating coupling by tuning its polarization state to the TE mode. Then the light is laterally coupled into an SSC through a cleaved single-mode fiber (CF). Because the optical outputs are standard single-mode waveguides, not SSCs, a lensed fiber is required to compensate for the relatively higher loss caused by waveguide-to-fiber mode mismatching. Finally, the light is collected by an optical power meter.

The measured normalized intensity as a function of wavelength is shown in Fig. 3(c). It is clear that the channel spacing of the proposed AWG router is ~ 16 nm and each channel spectrally covers at least six sub-channels which are corresponding to the wavelengths of the looped-back AWG. The central wavelengths of 1543.85 nm, 1545.45 nm, 1547.05 nm, 1548.65 nm, 1550.25 nm, 1551.85 nm are switched to the upper output path (Path-1) of the AWG router, and the measured losses are -30.2 dB, -26.1 dB, -25.4 dB, -21.2 dB, -25.6 dB and -26.5 dB respectively. The losses of wavelengths switched to Path-2 (1556.65 nm, 1558.25 nm, 1559.85 nm, 1561.45 nm, 1563.05 nm and 1564.65 nm) are -22.9 dB, -25.5 dB, -24.4 dB, -26.2 dB, -27.5 dB and -30.2 dB. The two highest power wavelengths (1548.65 nm and 1556.65 nm) correspond to non-looped AWGR paths and the others with relatively lower powers are looped-back paths. The measured loss includes -5.5 -dB fiber-to-waveguide coupling loss and the AWG router's filtering loss which can be mitigated by designing a larger port-bandwidth. From our previous work [9], excluding the -10 -dB loss from Path-1 to Out-1 (including two MMIs and one offset delay waveguide) and the -5.5 -dB coupling loss, the insertion loss of the AWG router is only -2 dB. The looped-back AWG has ~ -6.5 -dB power loss. For 1-by-2 ODN measurement, the minimum peak-to-null intensity difference is ~ 14.3 dB. One main contributor is the interference impact. Because the looped-back architecture is different from the normal AWG module in [6], for a given wavelength, the light is first split into different channels (same as non-looped AWG) and the

Fig. 4. (a) The measuring setup of the time delay response; (b) The measured time delay of the two optical output ports. MZM: Mach-Zehnder modulator; PBS: polarization beam splitter; PC: polarization controller; CF-in: the input cleaved fiber; LF-out: the output lensed fiber; PD: photodiode; VNA: vector network analyzer.

signal loops back and combine again, thus the measured light signal is the addition of vector signals from several neighboring paths (mainly two adjacent paths). When a wavelength located in the overlapping area of adjacent channels' responses, the interference effect becomes stronger. Besides, the polarization state and wavelength-sweeping resolution may also affect the measurement. However, it should be pointed out that these measured values (e.g. 14.3 dB) are not the channel crosstalk of AWG. The crosstalk is still < -25 dB [11]. This response is used to show the central wavelength of each looped sub-channel and its corresponding power loss.

By selecting a certain wavelength, a relative delay can be obtained. The measured time delay response of the proposed Bi-ODN is shown in Fig. 4. In Fig. 4(a), the 5-dBm optical carrier is first fed into a 40-GHz Mach-Zehnder modulator (MZM) via PC-1 which yields a power-optimized input. The MZM is modulated by a radio signal generated by a vector network analyzer (VNA) and biased at the quadrature point (~ 2.0 V). An EDFA is used to boost the power to 13 dBm. PBS and PC-2 are employed to align the polarization state as described in Fig. 3(b). Then the light is laterally coupled in and out through a pair of CF and LF. Finally, the light is detected by a photodetector and fed back to the VNA. The VNA sweeps a frequency range from 1 GHz to 10 GHz. Fig. 4(b) provides the measured normalized true-time delay of the Bi-ODN. First of all, the delay of Out-1 (Optical Out-1) is normalized to 0 ps. When the selected wavelength is located in Path-1 of the AWG router, Out-2 has positive delay compared to Out-1, and the relative delay is 10.00 ps (1547.05 nm), 16.94 ps (1545.45 nm), 19.69 ps (1551.85 nm), 23.60 ps (1550.25 nm), and -47.48 ps (1548.65 nm) respectively. The largest opposite delay comes from the non-feedback path where the light goes through the AWG once time. Similarly, by tuning the wavelength to Path-2, the light will firstly go to Out-2 then Out-1 and thus the time delay is negative. The accomplished stepwise

delays are -10.22 ps (1563.05 nm), -15.38 ps (1561.45 nm), -18.82 ps (1559.85 nm), -21.89 ps (1558.25 nm), and 48.57 ps (1556.65 nm). The designed tuning range is 12.5 ps. The measured values are 13.60 ps and -11.68 ps with errors of 8.8% and 6.56%, respectively. The extended positive and negative delays can realize resolution-doubled mm-wave beam steering as shown in Fig. 4(b) (dual-antenna system).

IV. SYSTEM EXPERIMENTAL SETUP

In this section, a 38-GHz fiber-wireless beam steering system is implemented to prove the effectiveness of the integrated ODN. As the resolution-doubled concept is already proved on chip-level, here, the system experiment only tests the positive time delays in order to simplify the system operation. The proof-of-concept 38-GHz mm-wave beam steering system is depicted in Fig. 5. A 10-dBm optical carrier is first fed into a 40-GHz MZM (MZM-a) via PC-1 which yields the power-optimized input. The MZM-a driven by a 19-GHz clock signal is biased at the null point to generate optical carrier suppression. Then the 38-GHz mm-wave carrier can be obtained by beating the two 19-GHz sidebands as shown in Fig. 5(a). After power compensation enabled by EDFA-1 (presented in Fig. 5(b)) and polarization state optimization via PC-2, a 2-GSa/s baud rate QAM-4 signal with 2-GHz radio carrier is modulated onto optical domain by a 10G-class MZM. This radio signal is generated by an arbitrary waveform generator (AWG-sig in Fig. 5). Before being delivered to the proposed Bi-ODN, the signal is pre-amplified to 12 dBm due to the high chip-loss. Two EDFAs (EDFA-3 and EDFA-4) are employed to make the power-balanced mm-wave signals, which are then detected by a pair of photodetectors. The required 38-GHz carrier frequency can be obtained after the optical-to-electrical conversion. The converted signals are amplified by two 40-GHz bandpass amplifiers (EA-1 and EA-2, bandwidth 36 GHz–40 GHz). EA-1 and EA-2 separately connect to two identical 38-GHz aperture antennas (Tx-1 and Tx-2) to spread the data signals wirelessly. The centre-to-centre distance between Tx-1 and Tx-2 is set as 40 mm and the receiving antenna (Rx) is put at the forward distance of 280 mm. By moving the Rx antenna laterally, the measurement at different lateral distances can be implemented. The power is measured by an electrical spectrum analyzer (ESA, 0–67 GHz) without amplification. For the data transmission part, the received QAM-4 signal is firstly amplified by a 38-GHz amplifier and is down-converted to baseband enabled by a mixer and a 38-GHz local oscillator with 23-dBm output power. Finally, the baseband signal is analyzed by a digital phosphor oscilloscope (DPO) to calculate the error vector magnitude (EVM). Fig. 5(c) is the 38-GHz mm-wave wireless communication link.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

For an arrayed antenna wireless system, the basic expression of the array factor can be presented as [9]

$$AF(\theta) = \sum_{n=1}^N I_n \exp(-j \times \beta \times n \times d \times \sin \theta) \quad (1)$$

Fig. 5. The proof-of-concept experimental setup of the 38-GHz mm-wave fiber-wireless link. (a) The optical spectrum before EDFA-1; (b) the optical spectrum after EDFA-1; (c) photos of the mm-wave wireless link.

Fig. 6. The measured power distribution of the two antennas.

where, θ is the arriving angle from Tx to Rx. N is the number of Tx antennas. B is the propagation constant and d is the spacing of Tx antennas. The assumption behind Eq. (1) is that the forward distance is much longer than the element antenna distance d , which results in the same arrival angle (θ). In our wireless link, the forward distance (280 mm) is not that long for the antenna spacing (40 mm). Thus the extra phase compensation is added in simulation. The engaged aperture antennas can be considered as semi-omnidirectional antennas. In our experiment, the distance of 40 mm between Tx antenna is much larger than one half of the wavelength (3.95 mm), thus the side lobes of the phased array antennas exist, resulting in more than one peak in the beam profile. It should be pointed out that the side lobes can be easily avoided by using patch antennas.

Firstly, the mm-wave power distribution of each antenna only transmitting 38-GHz carrier is measured in order to obtain the spatial spans of the two antennas in the lateral direction and the overlapping area. As shown in Fig. 6, the main lobe of each

antenna spreads around 17 cm and the overlapping area is only ~ 14 cm. Thus in mm-wave beam steering measurement, the selected measuring span is 15 cm (From -7.5 cm to 7.5 cm). For each antenna, the received average electrical power in the main lobe is ~ -28.65 dBm.

Fig. 7(a)–(b) present the simulated and measured 38-GHz mm-wave power versus the lateral offset (referred to as ‘X-axis offset’) curves transmitting single frequency signal (38-GHz carrier) without loading QAM-4 signal. In the simulation, the amplitude coefficients are set to 1 and 0.92 respectively according to the practical radio powers, and the average power is normalized to the received average values in the experiment. The lateral beam distribution spatially shifts when changing the phase difference converted from the time delay of the Bi-ODN. The phase shifts of the 38-GHz mm-wave are 67.57° , 132.54° and 186.02° respecting the relative delays of 6.94ps, 9.69ps, and 13.60 ps respectively. The peak moves from right side (x -axis = 0.5 cm) to left side (x -axis = -2 cm). The power difference between peak and null points is around 17 dB and the measured average peak power is ~ -22.50 dBm with 5.85 dB higher than the single antenna case, which perfectly matches the theoretical gain of 6 dB. We can clearly see that the phase shift between the measured red curve (1547.05 nm) and the green one (1550.25 nm) is almost π , which matches well with the simulation result ($\sim 186.1^\circ$ shift for 38-GHz mm-wave). Thus the very high accurate mm-wave beam steering system can be experimentally demonstrated by utilizing our designed Bi-ODN. In Fig. 7(c)–(f), the simulated and experimental results are separated to allow a better illustration of the trends. The measured power versus x-axis offset curve (dot) and its simulated counterpart (line) are presented one by one according to the wavelength. The experimental results match well with the simulated results in terms of peak/null locations and their periodicities.

Fig. 7. The received power versus x-axis offset curves.

Fig. 8. (a) The measured EVM curve; (b) the measured power distribution curve.

Then the data transmission performance is evaluated by loading QAM-4 signal and introducing an extra electrical pre-amplifier. The measured EVM values of the QAM-4 signal on 38-GHz mm-wave using 1551.85 nm is shown in Fig. 8(a). Fig. 8(b) is the measured power distribution after amplification. We can clearly see that the EVM curve agrees well with the power curves, indicating that the beam steering induced power variance affects the quality of the received QAM-4 signal enormously. When the mm-wave beam is directed to the receiving antenna, the EVMs can be 11.9% (x-axis = -1 cm) and the constellations are well converged as shown in the inset photo next to this point. As shown in Fig. 8(b), an around 18-dB power drop at the null point (x-axis = 1.5 cm) compared with the peak value. The received power is -8.2 dBm and the corresponding EVM number is reduced to 27.1%. The data rate of the QAM-4 signal is 4 Gbit/s.

VI. CONCLUSION

To conclude, a fully integrated, stepwise, wavelength-tuned, and optical mm-wave beamformer with doubled delay resolution is proposed and experimentally demonstrated in a generic InP platform. By introducing a small AWG router for positive/negative delay-mode selection, a resolution-doubled 1-by-2 ODN is realized without using any active control elements (e.g. heaters) at the local side, which is better beneficial to a remotely-controlled mm-wave beam steering system. Furthermore, the AWG router potentially allows multi-port wavelength switching

to support a scaled-up network. The fabrication-caused delay error of <1.1 ps is experimentally verified on-chip. A further proof-of-concept 38-GHz fiber-wireless beam steering system is experimentally demonstrated using QAM-4 modulation format. Accurate mm-wave phase shifts originated from the proposed optical beamformer are well matched to the simulation results, which proves the effectiveness of the tunable integrated beamformer.

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