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An Integrated Stepwise Tunable Optical mm-wave Beam Former with Doubled Delay Resolution

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Abstract *An integrated stepwise tunable optical mm-wave beam former with doubled delay resolution is proposed and ~1-ps delay imbalance is implemented. This technique also supports single-wavelength-tuned multi-beam steering. Moreover, two bidirectional hybrid couplers are investigated.*

Introduction

Indoor wireless traffic is getting congested because of the relentlessly growing demand for broadband mobile services[1-2]. Therefore, millimetre-wave techniques offering a high bandwidth attract lots of attention to solve the imminent wireless traffic crunch[3-4]. As a key technique in 5G, millimetre-wave beam-forming/-steering boosts capacity by exploring spatial channel multiplexing. However, the required lossless and broadband true-time delay functions are complex to realize electronically in a CMOS platform. In order to solve this problem, stepwise tunable optical delay networks (ODNs) have been introduced for indoor systems[5-6]. These integrated optical time delay lines (OTDLs) were realized with looped-back arrayed waveguide gratings (AWG), which are broadband, reliable (no active control device at the local site but remotely controlled by means of wavelength) and low cost. However, a key challenge is to increase the delay resolution, thus further increasing the number of spatial channels. Usually, the delay resolution is determined by the number of feedback loops inside an AWG.

In this paper we propose, based on a specially designed bi-directional ODN (Bi-ODN), a concept of double the delay resolution, by extending the positive delay to its negative counterpart. This integrated Bi-ODN is fabricated in a generic InP platform and experimentally characterized. The measured insertion loss (IL) of the 2-by-2 Bi-ODN is <17.5dB which includes the losses of a looped-back AWG (6.4dB), a bidirectional hybrid coupler (BHC, 7.94dB) and a multimode interferometer (MMI, 3dB). An imbalance of ~1ps between positive and negative delays has been implemented. This technique also supports single-wavelength tuning for steering multiple beams. Moreover, two passive BHCs are experimentally investigated.

Principle of the Bi-ODN

The principle of Bi-ODN for millimetre-wave beam steering is schematically shown in Fig. 1. Fig. 1(a) describes a looped-back AWG with four feedback paths, where the AWG acts both as a wavelength multiplexer and de-multiplexer by feedback loops connecting inputs and outputs. This architecture is topologically equivalent to two AWGs in series and therefore it is an almost half-sized and fabrication-tolerant design[5]. Here, a pair of input and output is selected as the bidirectional input/output of the looped-back AWGs and the delay is $t_0(\lambda_0)$. The feedback paths are set in increments of Δt. Fig. 1(b) depicts the delay response of the spectrum transmission

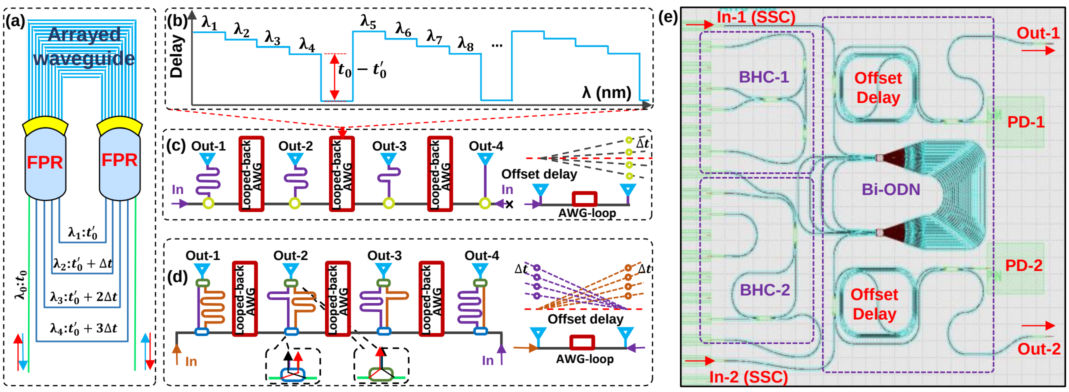

Fig. 1 (a) The looped-back AWG; (b) the spectral transmission of the looped-back AWG; (c) the positive-delayed ODN; (d) the principle of the Bi-ODN; (e) the mask layout of the Bi-ODN. FPR: free propagation region; SSC: spot-size convertor; BHC: bidirectional hybrid coupler; PD: photodiode. Bi-ODN: bidirectional optical delay network

of the looped-back AWG OTDL. Due to the spectrally cyclic characteristic, the delay response is also spectrally cyclic. In one period (from λ_1 to λ_4), each wavelength is split into different feedback loops and thus different delays.

However, the inherent large delay ($t_0 - t_0'$) between through-path and feedback loops causes spatially-uneven beam steering. In order to obtain a practical ODN, offset delays are needed before each output port. Fig. 1(c) presents the regular positive ODN, where the delay of each output is successively increased. This is a 1-by-4 network and each output is put at an individual offset delay line. When signal is fed into the right port, the delays at the four outputs are disordered due to the mismatched offset delays. The right part of Fig. 1(c) describes the delay response of a 1-by-2 ODN. The offset delay of Out-1 is set between t_0' and $t_0' + 3\Delta t$, here it is set as $t_0' + 1.5\Delta t$. Then the relative delays of Out-2 are $0.5\Delta t$, $-0.5\Delta t$, $1.5\Delta t$ and $-1.5\Delta t$, respectively. Thus the delay resolution is 4. In contrast, the resolution-doubled Bi-ODN is shown in Fig. 1(d). A specially designed passive BHC with bidirectional offset delay line structure replaces the regular couplers in Fig. 1(c). The dual-input ODN not only doubles the resolution using the same looped-back AWG, but also supports simultaneous multi-beam steering using a single wavelength. From the delay response of the 1-by-2 network, 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. When signals are separately fed into the ODN from different inputs at the same time, the ODN's output is the so-called radio multi-beam steering. Fig. 1(e) describes the mask layout of the 1-by-2 Bi-ODN. Two spot-size convertors (SSCs) at the chip inputs are used to enable better lateral fibre coupling. The coupled light is then split into two paths by a BHC, which includes two 2-by-2 MMIs. One path is for PD-1 (Out-1) with an offset delay. The other branch goes into the looped-back AWG and the output is also split via another MMI-based BHC. The output of PD-2 (Out-2) experiences a different offset delay. The symmetrical design allows a bidirectional operation. Out-1 and Out-2 are optical ports reserved for measurement, which can be removed in the final design.

Experimental setup and results

In this section, the measured results are shown and technically analysed. Fig. 2(a) presents the measurement setup of the two BHCs. The 5.00-dBm optical power generated by a laser is first amplified to 12.88dBm via an Erbium-doped fibre amplifiers (EDFA). A polarization controller (PC) is employed to allow the pure TE or TM polarization in order to get the minimum insertion loss. Then light is laterally coupled into waveguide through cleaved single-mode fibre (CF). The same CF is placed aiming to couple light from chip to fibre and finally the light is launched into a power meter. The mask layouts of the measured structures are shown in Fig. 2(b) and the tested ILs are provided in Table 1. First of all, the waveguide (WG) including 2 SSCs is measured as the reference and its IL is 2.51dB. Then move to the BHC-1, which is composed by two 1-by-2 MMIs and one 2-by-2 MMI. Since port 2 and 3 are functionally equivalent, we select port 3 as the output. The ILs from 1 to 3 and 4 to 3 are 9.18dB and 10.45dB, with 1.27dB power difference. Similarly, in BHC-2 design using two 2-by-2 MMIs, the ILs from 3 to 2 and 4 to 2 are 9.84dB and 10.38dB, which has smaller power imbalance (0.54dB<1.27dB). Excluding the SSC's IL, the pure losses are 6.67dB and 7.94dB for BHC-1, 7.33dB and 7.87dB for BHC-2. Therefore, BHC-2 has better performance. In Fig. 2(b), the right part shows the simplified BHCs that logically mapped to our design. This imbalance is mainly caused by the 2-by-2 MMI connected to outputs (PD and Out-1). In fact, in the final design, it can be replaced by 1-by-2 MMI, which allows a better bidirectional performance.

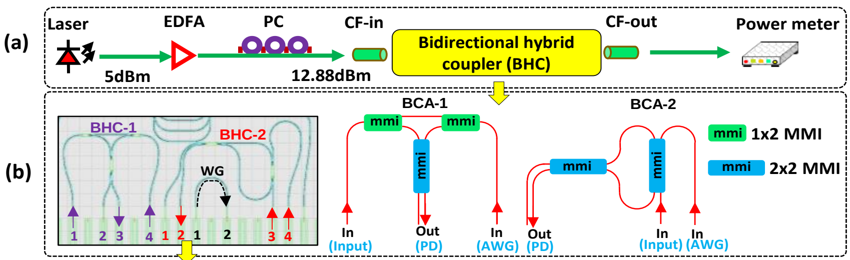

Table 1

Port a -> b	WG 1 -> 2	BCA-1 1 -> 3	BCA-1 4 -> 3	BCA-2 3 -> 2	BCA-2 4 -> 2
IL	2.51dB	9.18dB	10.45dB	9.84dB	10.38dB

Fig. 2 (a) the measurement setup; (b) the mask layout and the simplified logically mapping of the BHCs; Table 1: the measured ILs. CF-in: cleaved input single-mode fibre; CF-out: cleaved output single-mode fibre; WG: waveguide; BHC: bidirectional hybrid coupler; MMI: multi-mode interferometer

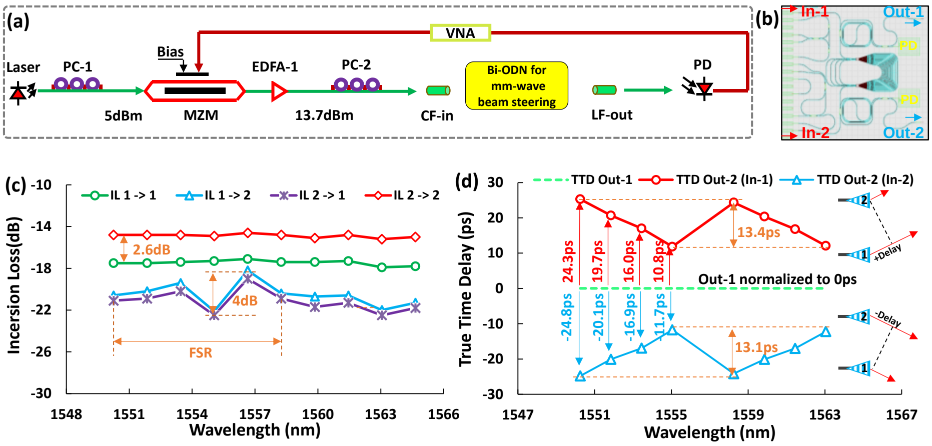

Fig. 3 (a) the measurement setup; (b) the mask layout of the Bi-ODN; (c) the measured insertion loss (IL) of the ODN. CF-in: cleaved input single-mode fibre; LF-out: lensed output single-mode fibre; PD: photodiode; VNA: vector network analyzer.

The measurement setup of the Bi-ODN is shown in Fig. 3(a). The 5.00dBm optical carrier is first fed into a 40-GHz Mach-Zehnder modulator through PC-1 which yields a power-optimized input. The MZM is modulated by the radio signal generated by a vector network analyser (VNA) and biased at quadrature point (~2.0V). An EDFA is used to boost the power to 13.70dBm. PC-2 is employed to align polarization. Then light is laterally coupled into waveguide through a CF. At the output port, a lensed single-mode fibre (LF) replaces the CF aiming to optimize the coupling. Finally, the light is detected by a PD and fed back to the VNA. The VNA sweeps a large frequency range from 1GHz to 20 GHz. The spectrum centre of the AWG is designed at 1550 nm and its free spectral range is 8 nm (1000GHz) with 1.6nm (200GHz) channel spacing[5]. The measured loss of the Bi-ODN (shown in Fig. 3(b)) is depicted in Fig. 3(c). From the results, there is a 2.6-dB loss difference between paths from In-1 to Out-2 (~17.5dB) and from In-2 to Out-2 (~14.9dB), which is mainly caused by the mismatch of the two offset delay lines. The loss-fluctuation of the cross paths (In-1 -> Out-2 and In-2 -> Out-1) is less than 4dB. Moreover, they have highly-consistent loss curves with <1dB difference, which is well matched with our design. Excluding the CF-chip-LF loss (usually >5dB), the measured loss of through path (In-1 -> Out-1) is 10dB including 6dB loss of a MMI and 2.25dB loss of an offset delay waveguide. The cross path (In-1 -> Out-2) experiences a <17dB loss which is comprised of the losses of MMIs (9dB), a looped-back AWG (6.4dB) and the waveguide. Fig. 3(d) provides the measured normalized true time delay of the ODN. First of all, the delay of Out-1 (for Antanna-1) is normalized to 0ps. When signal is fed into the ODN from In-1, the stepwise relative delays between Out-1 and Out-2 (for Antenna-2) are 24.3ps, 19.7ps, 16.0ps, 10.8ps. The maximum tuning range of Out-2 is 13.4ps which is a little bit higher than designed (12.5ps). When change the input port to In-2, the stepwise relative delays between Out-1 and Out-2 are -24.8ps, -20.1ps, -16.9ps, -11.7ps. The tuning range is 13.1ps. The extended positive and negative delays can realize resolution-doubled mm-wave beam steering as shown in Fig. 3(d) (dual-antenna system). An imbalance of ~1ps is experimentally implemented. The acceptable delay matches between positive and negative delays enable a higher-resolution beam steering.

Conclusions

Enabled by extending the positive delay with its negative counterpart, the delay resolution of the proposed Bi-ODN for millimetre-wave beam steering is doubled and demonstrated in a generic InP platform. Very small imbalance (~1ps) between positive and negative delays is implemented.

Acknowledgements

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