Power Monitoring and Thermal Crosstalk Compensation for ORR-based Optical Beamformer

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Abstract: We demonstrate thermal-crosstalk-compensated ORR-based beamformer on InP photonic integrated circuit, through an automatic voltage control method that uses on-chip power monitoring for continuous delay tuning, with <1s reconfiguration time. © 2024 The Author(s)

1. Introduction

Optical beamforming network (OBFN) technology provide advanced phase control for modern radar and point-to-point wireless communication systems [1]. The optical ring resonator (ORR) is a promising solution to overcome the electric delay to enhance the bandwidth and avoid signal distortion due to electromagnetic interference [2]. The photonic integrated ORR-based delay line can provide continue tuning of true time delay (TTD) of the signal with on- and off-resonate operation, which can achieve on- and off- resonate delay in ns [3] and 100's ps [4], respectively. TTD will be applied to the signal path feeding to the elements of a phased-array antenna (PAA), resulting in radio frequency (RF) beams pointed to a single or multiple users and tracking the users to keep them connected. Therefore, updating the control scheme to realize the tuning of beam steering angle is of importance for the operation of integrated ORR-based true time delays. So far, the beam pointing control is mostly done by adjusting the voltage level of individual heaters according to a look-up table [1,2], which is suitable for a static and semi-mobile or nomadic user. However, if users move, then the look-up table must be updated with new values according to their speeds and direction, as shown in Fig. 1(a). An automatic, accurate, and fast beam tracking and pointing control is needed to provide seamless connectivity to mobile users. Moreover, the tree structure and the split-combine elements in the MZI induce large loss to the optical delay paths [2,5]. The InP platform is a matured platform that offers monolithic integration of active and passive photonic components [6]. In our work, we exploit the on-chip InP semiconductor optical amplifier (SOA) to compensate the path loss on the optical delay as well as to enable on-chip power monitoring [7]. With the on-chip power monitor, we can easily characterize the response of the fabricated ORR-TTD with an external tunable laser.

In this work, a 2-ORR structure is employed to tune the pass bandwidth as well as the true time delay of the optical path. Having characterized the ORR response, we adapt the ORR-TTD model [8] to simulate the voltage to ORR output relation. We propose a thermal-crosstalk-compensated method for direct voltage-to-phase control of the phase shifters, developed from thermal eigenmode decomposition [9]. We experimentally demonstrate the automatic tuning of TTD of the 2-ORR PIC, while maintaining the center wavelength on the resonate wavelength. The method is promising for simple characterization and control of large-scale optical beamformer chip, without look-up tables.

2. Control Method and Experimental Setup

Fig. 1(b) depicts the schematic of elements and their thermal coupling on the 2-ORR TTD chip. The fabricated InP chip includes 2 ORRs with individual Mach-Zehnder interferometers (MZIs) for controlling the coupling coefficient, and there is a SOA used as power monitor to detect the output power. The phase shifter ϕ_1 and phase shifter ϕ_2 are for the control of phase in the optical ring while phase shifter 3 and 4 are for the control of optical delay by tuning the

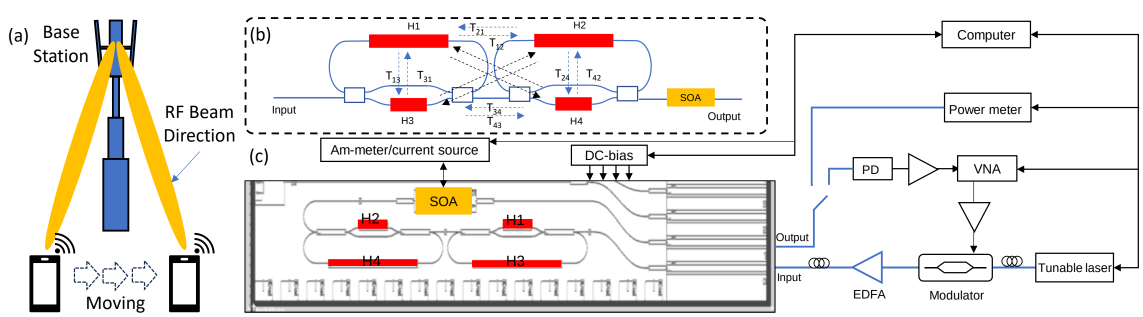

Fig. 1. (a) Phased-array antennas in a base station tune their main beam to a moving user, (b) schematic of the 2 ORR-TTD integrated circuit and (c) the experimental setup.

coupling coefficient κ_1 and κ_2, with thermal tuning by heater 1 to 4 as indicated as H1, H2, H3 and H4, in Fig. 1(b). Due to the thermal crosstalk, the heaters will have bidirectional heat transient. The heat influence from one element i to another element j is denoted as T_{ij}, as shown in Fig. 1(b). These thermal transient coefficients will form a 4×4 matrix $\boldsymbol{T}$ in case of 4 heaters, which is commonly used in the thermal eigenmode decomposition [9]. On the other hand, the voltage-to-phase response of the heaters are different attributing to different metal lengths and possibly fabrication variations. The phase change of the phase shifter is proportional to the heater power, which can be express as $\delta\varphi_i = a_i P_i$, where a_i is the response coefficient and P_i is the heater power. Assuming the resistance of the heater is constant, the phase change yields $\delta\varphi_i = a_i/R_i \cdot U_i^2$, with R_i being the resistant and U_i, the driving voltage. Due to the thermal crosstalk, the total change of the phase includes the heat contribution from other heaters: $\delta\widetilde{\varphi}_i = \Sigma T_{ij}\delta\varphi_j = \Sigma T_{ij}\, a_j/R_j \cdot U_j^2$. Let $C_{ij}=T_{ij}a_j/R_j$ and $V=U^2$, we get $\delta\widetilde{\varphi}_i = \Sigma C_{ij}V_j$. Use the matrix form, $\delta\widetilde{\boldsymbol{\varphi}} = \boldsymbol{CV}$, where $\boldsymbol{C}$ is an $n\times n$ matrix, with n heaters, representing the thermal cross-talk and the individual voltage to phase response, and $\boldsymbol{V}$ is an $n\times 1$ vector. Hence, the desired driving voltage can be obtained with given phase changes $\delta\widetilde{\boldsymbol{\varphi}}$ and the response matrix $\boldsymbol{C}$. The optical time delay is defined by the coupling coefficient therefore the extinction ratio (ER) of the ORR transfer function, which will define the phase against the laser centre wavelength. So, $\delta\widetilde{\boldsymbol{\varphi}}$ can be calculated with ORRs modelling [8] and characterization of the resonance response of the ORRs.

To understand the thermal cross-talk, we record the spectrum response of the 2-ORR TTD. The experimental setup is illustrated in Fig. 1(c). An external tunable laser is exploited to measure the response of the race-track ORR. The heaters H1, H2, H3 and H4 are connected to DC power suppliers, which are controlled by the computer. For recording the transmission spectrum of the ORRs, the tunable laser is tuned from 1549.7 to 1550.2 nm with 0.01 nm steps and a fixed power of 3.7 dBm. The on-chip SOA is utilized as a photodetector, connecting to an ampere-meter, after calibration with input and output optical power. An external power monitor is used to verify the response at the output when the SOA is biased with a current source. A vector network analyzer is used to measure the phase response of the 2-ORR TTD chip and the time delay is calculated via the phase response on the resonate wavelength.

3. Results

Fig. 2(a,b) show the measured transmission spectrum of the 2-ORR TTD, individually tuning voltage on heaters H1 and H3. For the in-ring phase shifter, it is tuned from 1.4 to 5V with 0.1V per step, with all other heaters off, with the tunable laser scanning in 0.01 nm steps. For increasing the voltage of the heaters, the resonates of the ORRs are shift to the longer wavelength. The ER of the ORR is 6.7dB. Fig. 2(a) shows that there are two groups of power dip (indicated with blue) shifts. The faster changed tracks (indicated with ORR1) are from the ORR on the effective ring under tuning, while the slower changed tracks (indicated with ORR2) of dip shift are from the other ORR, which is influenced by a fraction of heat coupled from heater H1. The phase shift versus voltage square defines the C_{11} and C_{12}, and we observe negligible changes in the ER when tuning H1, therefore C_{13}, C_{14} are both 0. Fig. 2(b) shows that the ER increases to maximum when voltage of H3 is set from 1.4 to 2.5V, i.e. increasing the couple coefficient of the ORR, reaching to 14dB. Then it decreases attributing to the further increase of the coupling coefficient with the coupling MZI to maximum at 3.7V, which defines the C_{33}. The resonate wavelengths shift due to the thermal cross-talk from H3, to the race track waveguides of the ORRs, based on which we can define C_{31} and C_{32}. Other matrix

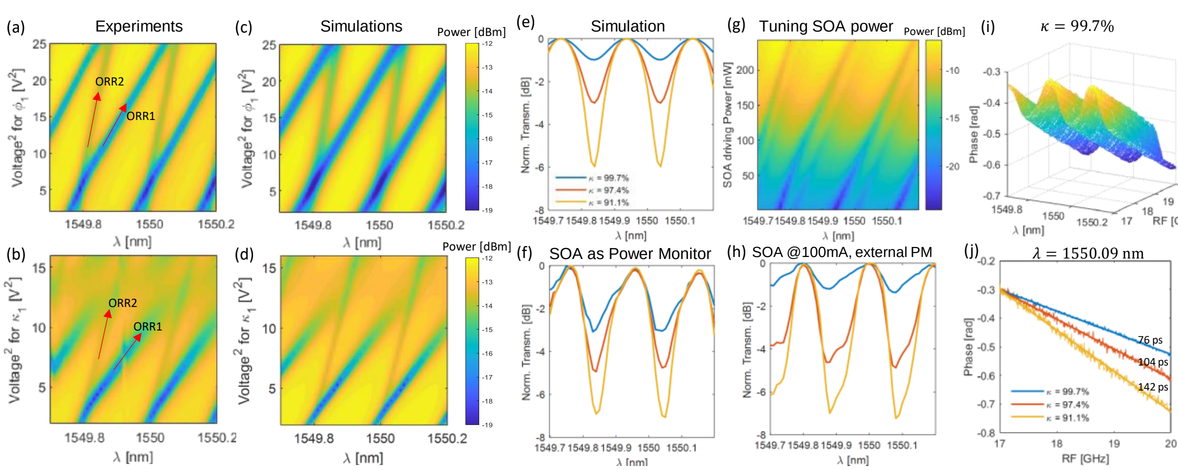

Fig. 2. Transmission spectrum of 2-ORR TTD in (a-b) experiments and (c-d) simulations. And automatic control of optical delay with fixed center wavelength, (e-h) output spectrum and (i-j) RF response measurements.

elements C_{21}, C_{22}, C_{41}, C_{42} and C_{44} can be obtained in the same way. Fig. 2(c,d) shows the simulations on the response of 2-ORR TDD using the ORR TTD modelling and with the measured response matrix $\boldsymbol{C}$. The simulation is used to calculate the desired phase shift $\delta\,\widetilde{\boldsymbol{\varphi}}$ for the 2-ORR TDD for the target bandwidth and time delay. The determination of response matrix $\boldsymbol{C}$ may be further simplified by using neural network-based algorithms.

Fig. 2(e,f) shows simulation and experimental results of automatic voltage control using solutions of $\delta\,\widetilde{\boldsymbol{\varphi}} = \boldsymbol{CV}$. Fig. 2(e) shows the change in ER of the 2-ORR by tuning the from 99.7% to 91.1% to achieve different ER. Fig. 2(f) depicts the SOA monitored ORR output when the solution voltages of $\boldsymbol{V}$ are applied to the 4 heaters, with the unaffected centre wavelength at 1550.04nm. When SOA is biased with the current source, it will contribute the heat to the ORR, but we can measure the dip shift respecting to the SOA driving power, as shown in Fig. 2(g). The SOA shift the resonate wavelength of 0.05nm, and the thermal contribution to the 2 ORR is similar. We can also see this shift when SOA is set to 100 mA, as shown in Fig. 2(h), tuning the same κ as in Fig. 2(f), where the resonate wavelength shifts from 1550.04 to 1550.09nm. Then the true time delay of the ORR chip is assessed with the RF response measurement with a VNA, sweeping frequency from 17 to 20 GHz. Fig. 2(i) shows the phase response of the ORR-TTD chip, when κ is set to 99.7% and tuning the laser wavelength. The response of the phase is following the spectrum of the ORR chip output. Fig. 2(j) shows the measured phase response of the 2 ORR-TTD with a fixed laser wavelength at 1550.09nm, and tuning the κ from 99.7% to 91.1%, resulting in optical time delays from 76 to 142 ps, agreed with the ER variation in Fig. 2(f) with the SOA power monitoring. The desired voltages obtained by the proposed method takes 0.4s in calculation, and they are driven on the heater via the DC power supplier, which takes 0.6s in communication and configuration. These can be improved with a specially designed driver and processor. After the configuration, it takes 0.75s to reach the thermal equilibrium, resulting in 1.75s in correctly automatic configuration. If we use other algorithms, this would be the time for one iteration and depending on the complexity of the algorithm, this time may be longer. Nonetheless, together with on-chip power monitoring, the control mothed is feasible to enable thermal cross-talk compensation without a look up table, which will be beneficial for a large scale optical beamforming network.

4. Conclusions

We demonstrated thermal crosstalk compensated automatic voltage control of the InP based 2-ORR TTD photonic integrated circuit for continue tunable optical time delay, with an output SOA enabling ORR-TTD on-chip power monitoring and providing optical gain. The voltages to drive the TTD chip are obtained by solving the linear equation of thermal cross-talk compensated voltage-to-phase response matrix, with given target phase shift, determined from the ORR characterisation. The control method achieved to tune the optical time delay while keeping the wavelength at the same value. The performance of the voltage control may be optimised with more precise characterisation or combining with control algorithms. This method provides a simple approach to control the ORR-TTD based optical beamformer without a look-up table to determine its beam pointing angle. This automatic control will enable us to effectively control large PAAs where a large number of phase shifters must be controlled and updated to track the movement of mobile users.

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5. References

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