InP Photonic Integrated Circuit with On-chip Monitors for Optical Beam Steering

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Abstract: Optical beam steering controlled by an array of phase shifters from an InP photonic integrated circuit has been demonstrated with the help from on-chip monitors.

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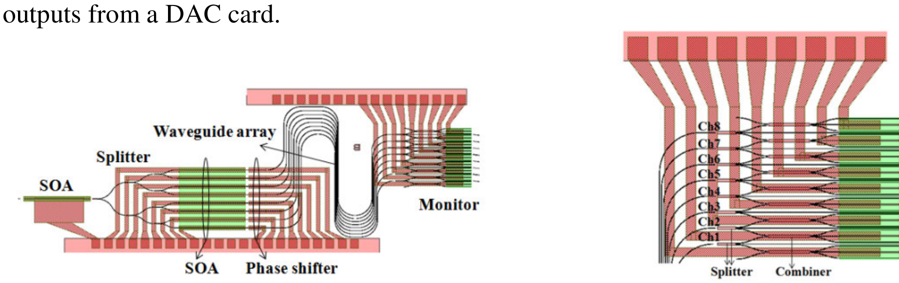
1. Introduction

Electronically controlled optical beam steering is potentially useful for a number of applications such as light detection and ranging (LIDAR), 3D imaging, precision targeting, guidance and navigation, etc. Recently, we have demonstrated an InP photonic integrated circuit (PIC) for 2D optical beam steering controlled electronically [1]. The critical part of the PIC is an optical waveguide array with embedded 2nd-order gratings for out-of-plane emission. An array of phase shifters is used to generate a phase slope across the waveguide array which steers the beam perpendicularly to the waveguide (lateral direction). The embedded 2nd-order gratings have the emission angle dependent on wavelength, which is used to steer the beam along the waveguide by varying the input wavelength (longitudinal direction). The 2D beam steering has thus been achieved by controlling the input wavelength and the array of phase shifters simultaneously. In our first demonstration, the beam is steered to different angles in the lateral direction by blindly optimizing the phase shifter bias currents through the particle swarm optimization (PSO) algorithm [1]. This would become tedious if sweeping with very small angle steps is required. It becomes even more problematic if the currents injected into the phase shifters need to be re-optimized when changing wavelength. In this work, we show that through integrated on-chip monitors the phase shifters can be characterized on-site, so the dependence of the generated phase shift on injected current, i.e. the phase-current curve, can be established. Then the phase slope across the array required by a specific steering angle can be set directly by referring to the established phase-current curves.

2. PIC layout

Fig.1 (a) shows the layout of the PIC which consists of the input semiconductor optical amplifier (SOA), the 1×2 MMI tree which splits the input into eight channels, an SOA array and a phase shifter array which are used to boost the power and control the phase of each channel, then the waveguide array with embedded 2nd-order gratings for the out-of-plane emission, and the monitor array. Additional bends are added to make each channel have equal length in order to prevent additional differential phase generated when changing wavelength. Fig. 1 (b) shows the blown-up of the monitors. Each channel is split into three equal parts by a 1×3 MMI. Two close parts from two adjacent channels are combined by a 1×2 MMI to form interferometers with the interference monitored by a photodiode (PD) as seen from Fig. 1 (b). Two additional waveguides are added at the output interface of the MMI to guide away the destructive interference so as to increase the interference extinction ratio. For the following measurement we bias the SOAs at 100 mA each. The input wavelength is fixed at 1540 nm. The 8 phase shifters are controlled by 8 current analog outputs from a DAC card.



(a) (b)

Fig. 1 (a) Layout of the PIC; (b) Blown-up of the monitor array

3. On-site characterization of the phase shifters

For on-site characterization of the phase shifters, we fix the current injected into the i^{th} channel phase shifter at 1 mA and increase the $(i+1)^{th}$ channel phase shifter current from 1 mA to 20 mA and then record the i^{th} PD signal. The channels and PDs are numbered as shown in Fig. 1 (b). The results are shown in Fig. 2 (a) as dashed curves with i from 1 to 7. Then we fit these curves with a theoretical model to find the phase $\Delta\phi_i(I)$ which is the phase of the $(i+1)^{th}$ channel relative to the i^{th} channel when the i^{th} channel phase shifter is injected with 1 mA current. Equation (1) represents the model where C_i, i from 0 to 4, are fitting parameters, $\Delta\psi$ represents the initial phase difference. The fit is shown in Fig. 2 (a) as solid lines.

$$\begin{aligned} V(I) &= C_0\left[1+\exp(-2\alpha)+2\exp(-\alpha)\cos(\Delta\phi)\right]+C_1 \\ \Delta\phi &= \Delta\psi + C_2\sqrt{I} + C_3 I, \quad \alpha = C_4(\Delta\phi - \Delta\psi) \end{aligned} \qquad (1)$$

We repeat the above process for all the channels. The reference phase for the series of phase curves $\Delta\phi_i(I)$, i from 1 to 7, is not unified. We can make them all refer to the first channel when its phase shifter is biased at 1 mA. To achieve this we just need to move the curve $\Delta\phi_i(I)$ vertically according to $\phi_{i+1}(I) = \Delta\phi_i(I) + \sum_{j=1}^{i-1}\Delta\phi_j(I = 1\,\text{mA}), i = 1...7$.

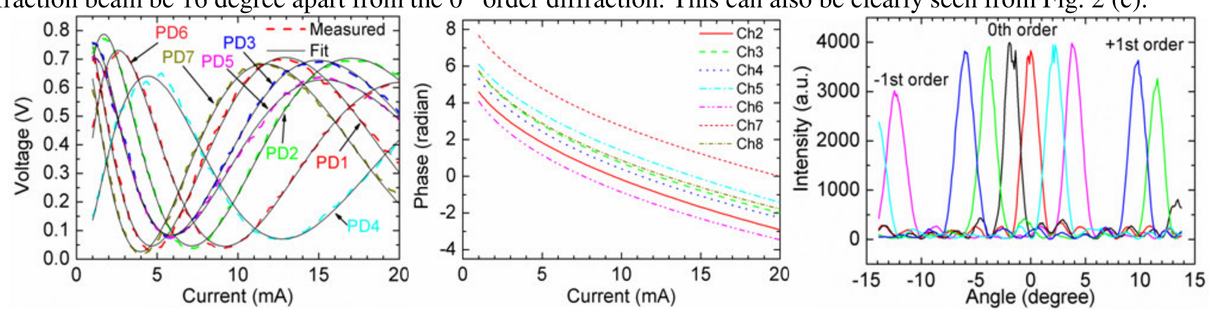
$\phi_1(I)$ is zero because the first channel refers to itself. $\phi_i(I)$ is the phase-current curve we obtain through on-site characterization of the phase shifters.

4. Calibrating the phase-current curves

Once we have the phase-current curves for all the phase shifters, we can steer the beam by setting the phase slope across the waveguide array directly. For the beam to point to angle θ, we need a phase slope of $\phi_i = 2\pi(i-1)d\sin(\theta)/\lambda$, where d is the array pitch and λ is the wavelength. First we make the angle θ equal to zero. From the phase-current curves we have just obtained, we find a set of currents I_i which are suppose to make each channel have the same phase. But the far-field pattern is not very good as we set these currents because of two reasons: 1) the phase error accumulation which is produced when we move the phase reference from adjacent channels to the first channel; and 2) not necessarily equal phase across the array makes a good pattern pointing at angle 0 because there could be variations from grating to grating. To handle these issues we optimize the far-field pattern around the current sets I_i through the PSO algorithm. A new current set I'_i has been found which are not far away from the original I_i but generates far better far-field pattern. Based on this we calibrate our original phase-current curves according to $\phi'_i(I) = \phi_i(I) - \phi_i(I'_i)$ which makes the new curves have nominal zero phase at I'_i. The new phase-current curves $\phi'_i(I)$ are the basis of our beam steering and are shown in Fig. 2 (b).

5. Beam steering

To steer the beam, we just need to find out the currents from the calibrated phase-current curves according to the phase required by the formula $\phi_i = 2\pi(i-1)d\sin(\theta)/\lambda$. Fig. 2 (c) shows the far-field distribution when the beam is steered from -6 degree to 4 degree with a step of 2 degree. The plot shows that the good beam shape and side-lobe suppression has been kept when we steer the beam. The waveguide array pitch is 5.5 µm which makes the $\pm 1^{st}$ order diffraction beam be 16 degree apart from the 0^{th} order diffraction. This can also be clearly seen from Fig. 2 (c).



(a) (b) (c)

Fig. 2 (a) PD response v.s. phase shifter current (b) Phase-current curves (c) Far-field pattern in the lateral direction

6. Summary

In summary we have demonstrated beam steering with the help from on-chip monitors. These monitors help establish the phase-current curves of the phase shifters. The beam is thus steered by setting the phase slope across the array directly.

7. References

[1] W. H. Guo, P. R. A. Binetti, C. Althouse, A. Bhardwaj, J. K. Doylend, H. P. M. M. Ambrosius, L. A. Johansson, and L. A. Coldren, "InP photonic integrated circuit for 2D optical beam steering," Post-deadline paper, IEEE Photonics 2011 (IPC11), Arlington, Virginia, USA, 2011.