Demonstration of low differential phase noise for optical phased arrays with optical amplification

B.S. Vikram[1], Marco Gagino[1], A. Millan-Mejia[2], L. Augustin[2], K.A. Williams[1],
V. Dolores Calzadilla[1,3]

[1] Technical University Eindhoven, Dept. of Electrical Engineering, Groene Loper 19, 5612 AP Eindhoven, The Netherlands
[2] SMART Photonics, High Tech Campus 29, AE Eindhoven, The Netherlands
[3]Photonic Integration Technology Center, Groene Loper 19, 5612 AP Eindhoven, The Netherlands

Optical phased arrays (OPAs) are key enablers for light detection and ranging (LiDAR) in autonomous vehicles, free space optical communications, imaging and coherent beam combining. Active OPAs (with amplitude and phase control) allow the control of individual channel gains along with phases for enhanced control of far-field beam pattern. Path length variations and noise from amplifiers degrade the differential phase noise between the OPA channels, which is a key performance indicator that determines the far-field performance in terms of power in the main lobe, extinction of side lobes and pointing error. Conventionally, in fiber-based platforms, multiple phase locked loops are required to reduce the differential phase noise by locking the channels.

In this work, we investigate the differential phase noise in an InP active OPA and demonstrate less than 10 mrad differential phase noise corresponding to a stability better than λ/600. To the best of our knowledge, this is the first demonstration of low differential phase noise in an active OPA with amplification in a photonic integrated platform. This result enables on-chip OPA amplification in the InP platform without active locking, thus reducing the system complexity and power consumption.

Introduction

Optical phased arrays (OPAs) facilitate agile scanning of the optical beam while avoiding the moving parts that limit the speed and reliability. The beam steering capabilities of OPAs are utilized in light detection and ranging (LiDAR), free space optical communications (FSO), and for power scaling through coherent beam combining (CBC). In comparison to passive OPAs providing only phase control of each element, active OPAs (i.e., with optical amplifiers) allow amplitude and phase control of each element. The addition of amplitude control allows improved control of far-field beam pattern and aids in adaptive ranging. However, the noise added by the amplifiers and the path length fluctuations between the array elements deteriorates the phase noise, reducing the temporal correlation between the OPA elements. The deterioration, described by the differential phase noise between the OPA elements, degrades the side lobe suppression ratio of the far-field beam.

Conventionally, optical phase locked loops (OPLLs) [1], [2] are employed in aperture channels in fiber based OPAs to mitigate the degradation. As the number of elements in the OPA increase, multiple OPLLs[3] are required, significantly increasing the complexity and cost of the system. Integrated photonics has the potential for reducing the differential phase noise owing to reduced path length fluctuations between closely spaced elements in a photonic integrated circuit (PIC). OPAs can be implemented in various PIC platforms such as Silicon (Si) [4], Indium Phosphide (InP) [5], and Silicon Nitride (SiN) [6]. Among these, InP allows implementation of active OPAs with semiconductor optical amplifiers (SOAs) in each channel. The additional phase noise generated from carrier density fluctuations and amplified spontaneous emission (ASE) from the SOAs along with the path length fluctuations on the chip will determine the far-field properties.

In this work, we report, to the best of our knowledge, the first measurements of differential phase noise in InP PICs. The measured differential phase noise (<10 mrad) corresponds to a stability of better than λ/600 between the OPA elements, and is achieved without the use of OPLLs. Analytical equations are used to evaluate the negligible deterioration of the far-field beam.

Experimental Setup

The measurement setup including the driving sources, the PIC and the measurement equipment is shown in Figure 1. An external laser source (100 kHz, Keysight 81960A) drives the PIC whose temperature is maintained at 18^{o} C. The edge-coupled signal, amplified by a booster SOA (driven at a current density of 5 kA/cm^2), is subsequently distributed among the individual OPA elements by a star coupler. Each element consists of a phase modulator (PM) and a channel SOA (driven at 5 kA/cm^2) which provide the phase and amplitude control respectively. An RF signal source (3 MHz) drives one of the PMs, frequency shifting the signal to obtain a heterodyne beat between two channels; no signal is applied on the other. A network of multi-mode interference (MMI) couplers is used to extract the beat signal between two adjacent channels, and is measured by an electrical spectrum analyzer (ESA) to extract the differential phase noise.

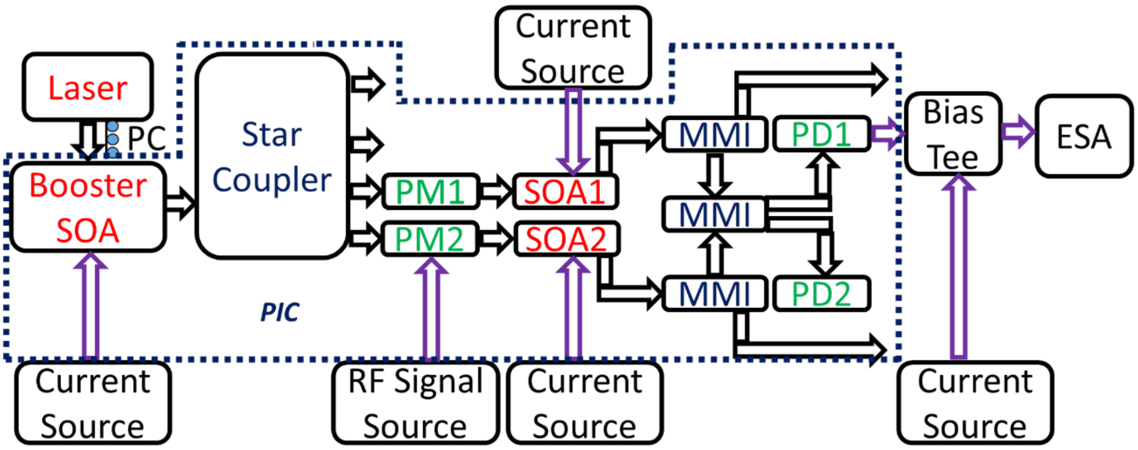

Figure 1 Schematic of the setup showing the sections of chip utilized for differential phase noise measurements. VOA-variable optical attenuator, SOA-Semiconductor optical amplifier, MMI-multimode interference coupler, PM-phase modulator, ESA- Electrical spectrum analyzer, PD-photodiode, PC- polarization controller.

Results

The differential phase noise spectra measured with the laser operated at 1550 nm is shown in Figure 2. The differential phase noise rises at the rate of ~30 dB/decade between 10 kHz to 100 kHz indicating that the temporal phase fluctuations between the two paths have reduced correlation. The rate falls to ~2 dB/decade below 10 kHz indicating highly correlated temporal phase fluctuations between the two paths. The RMS differential phase noise (obtained from integrating the plot from 100 Hz to 1 MHz) is less than 10 mrad across the C-band which is equivalent to a stability better than λ/600.

Figure 3 shows the influence of differential phase noise on the far-field beam pattern that is evaluated using equations (1-2) [7] for the case of emitters (100 elements, 2.2 µm spaced) with uncorrelated phase errors.

$$I_G^{unpert} = \frac{sin^2(\pi N\theta d/\lambda)}{sin^2(\pi\theta d/\lambda)} \tag{1}$$

$$I_G^{uncorr} = \exp(-\sigma_\phi^2)\, I_G^{unpert} + N(1 - \exp(-\sigma_\phi^2)) \tag{2}$$

Here, N is the number of channels in the array, θ is the angular position, d is the channel spacing, λ is the wavelength, σ_ϕ is the RMS phase noise, I_G^{unpert} is the unperturbed (ideal) far-field intensity, I_G^{uncorr} is the far-field intensity with uncorrelated phase errors. When the differential phase noise is 10 mrad, the influence on the far-field beam pattern is minimal. Significant deterioration is expected when the differential phase noise is in the range of several hundreds of milliradians.

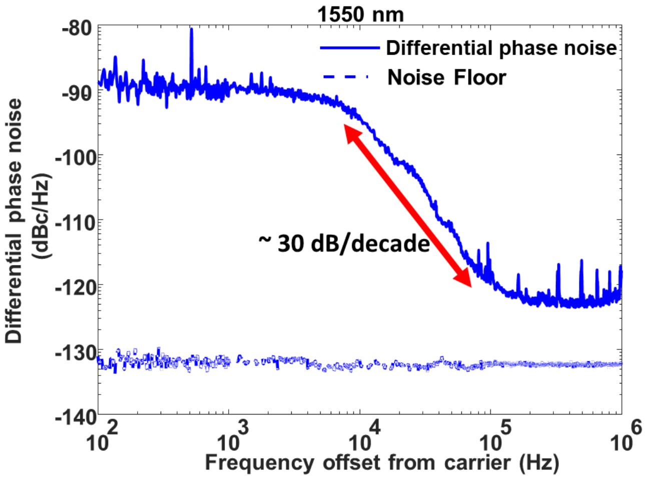

Figure 2 Differential phase noise spectrum with the source laser at 1550 nm along with measurement noise floor.

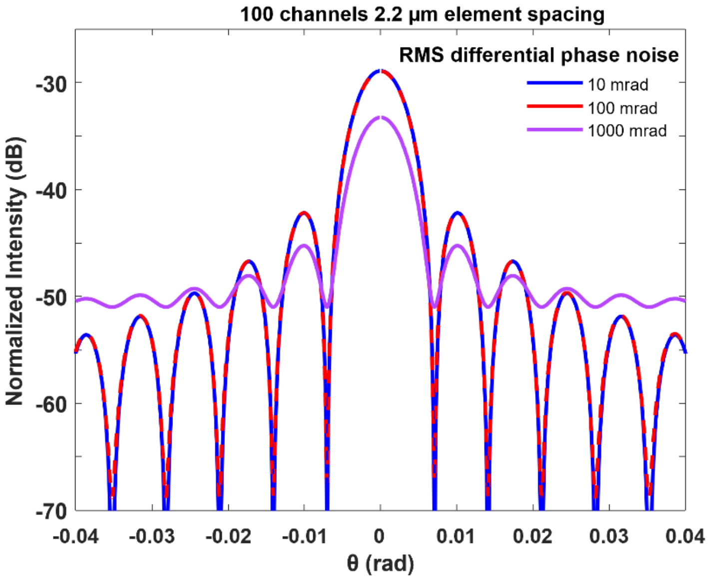

Figure 3 Impact of differential phase noise on far-field beam pattern for a 100 channel OPA with 2.2 µm spacing.

Conclusions

We report a low differential phase noise (<10 mrad) between active OPA channels in an InP PIC without any active locking. These initial results indicate the future potential of InP PICs for scalable active OPAs with reduced complexity and power consumption.

Acknowledgment

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