Integrated Silicon Nitride Optical Beamforming Networks for Wideband Communications

Yuan Liu\(^1\), Fengqiao Sang\(^1\), Brandon Isaac\(^2\), Jean Kalkavage\(^3\), Eric Adles\(^3\), Thomas Clark\(^3\) and Jonathan Klamkin\(^1\)

\(^1\)Electrical and Computer Engineering Department, University of California, Santa Barbara, CA 93106
\(^2\)Materials Department, University of California, Santa Barbara, CA 93106
\(^3\)The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723

Email: yuanliu@ucsb.edu

Abstract: Two approaches to ripple free 1 × 4 optical beamforming networks are presented; one is based on a 5-stage Mach-Zehnder switchable delay line and the other on a 3-optical-ring-resonator delay line. Both are demonstrated for W-band communications.

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1. Introduction

Integrated microwave photonics (IMWP) optical beamforming networks (OBFNs) are highly attractive for high frequency phased array antennas due to their low loss, large true time delay (TTD) bandwidth, and the ability to build large scale OBFNs [1]. Integrated tunable delay lines, the key elements of OBFNs, are realized with two primary approaches. The first is a Mach-Zehnder interferometer based switchable delay line (MZI-SDL), in which the delay is tuned by switching between delay lines with various lengths [2]. This method requires relatively simple control, but exhibits limited delay resolution. Also, optical switch imperfections may induce delay ripple, which could deteriorate the true time delay quality. The other approach utilizes all pass filters such as optical ring resonators (ORRs) [3]. This approach is characteristic of a small chip footprint and the continuous delay tuning. In this work, we implemented 1 × 4 OBFNs with both approaches and using ultra-low loss silicon nitride waveguides [4]. A new MZI-SDL topology was employed to eliminate delay ripple. For the ORR based OBFN, the tuning was optimized to achieve a flat TTD response, wide tuning range, and wide bandwidth.

2. Switchable Delay OBFN

A typical architecture of an integrated SDL is shown in Fig. 1. A balanced MZI is employed as a switch for each stage determining to pass through or skip the delay. For a traditional MZI-SDL, a binary-bits delay scheme (i.e. \(\tau_n = 2^{\tau_{n-1}}\)) is used to maximize the flexibility of the SDL. However, this requires a perfect switch for routing the entire optical signal in/out of the delay. Realizing and maintaining a coupling ratio, \(\kappa\), that is precisely 0.5 is difficult due to fabrication variation and operating temperature instability. If the signal is not entirely routed in the cross state two signal with differing delays will mix at the output and cause delay ripple and suboptimal beam steering. Figure 2(a) and 2(b) show the simulation results for a normalized delay and power spectra for various \(\kappa\) for a 3-stage binary-bits SDL (\(\tau_3 = 2\tau_2 = 4\tau_1\)) in the worst case scenario. When \(\kappa = 0.35\), the peak-to-peak ripple is twice the desired delay. However, in the pass-state, the MZI switch is able to 100% route the optical signal for any \(\kappa\). Building on this, we propose a new ripple-free topology whereby all the delay elements have equal length. Only one of the switches is in the cross-state, and all others are in the pass-state. As a result, there will be no mixing of differently delayed optical signals and the switch set to cross-state determines the delay of the SDL. We implemented four 5-stage ripple-free MZI-SDLs to form a 1 × 4 OBFN and the delay elements are designed as \(\tau = 4.2, 2.8, 1.4\) and 0 ps, to perform 0 ∼ 90°
beam steering for a 90 GHz signal. Figure 2(c) shows the measured delay response of one path over 1.5 nm with \( \tau = 4.2 \) ps. The data was smoothed to eliminate measurement noise. Since the ripple amplitude doesn’t change with delay, we believe that these ripple observed is due to the measurement itself or some unknown resonance on the chip. Figure 2(d) shows a 10 Gbps signal delayed by 21 ps.

### 3. Optical Ring Resonator OBFN

A 1 \times 4 3-ORR based OBFN was also realized, as depicted in Fig. 3(a). A ORR comprises a balanced MZI coupler and the feedback waveguide. The resonant frequency and coupling coefficient can be thermally tuned, which should be optimized so that the sum of each ring’s delay response in the delay line can realize a flattened TTD response. A genetic algorithm was applied for the optimization and a look-up table is used for optimized ring tuning. The optimization also reveals a tradeoff between TTD flatness (ripple), bandwidth, and delay as shown in Fig. 3(b). Figure 3(c) shows the optimized TTD delay response of 3-ORR delay line demonstrating a bandwidth of 8.7 GHz. Without any noticeable ripple, a tuning range of 172.4 ps was achieved, which corresponds to a phase shift of 37.5\( \pi \) for a 90 GHz signal. Figure 3(d) shows the eye-diagram of a 3 Gbps signal delayed by the 3-ORR delay line, where open and clear eyes are preserved and the eye shift is consistent with the delay responses shown in Fig. 3(c).

### 4. Conclusions

Two different integrated OBFNs using ultra-low loss silicon nitride waveguides were demonstrated; one is a ripple-free 5-stage MZI-SDL and the other is a 3-ORR delay line. The MZI-SDL demonstrated a maximum delay of 21 ps, TTD bandwidth over 1.5 nm, and discrete delay tuning with a 4.2 ps interval. The 3-ORR delay line demonstrated a 172 ps continuously TTD tuning range, but with 8.7 GHz of bandwidth. Both implementations are promising for W-band beam steering. A complete OBFN characterization and 90 GHz beam steering experiment will be performed in the future.

### References


