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Temperature Stabilization Technique for Si Micro-Ring-based Coherent QPSK Transmitter

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Abstract

A temperature stabilization technique is demonstrated for a Si micro-ring-based coherent transmitter operating at 25-Gbaud QPSK. The technique provides initial bias optimization and real-time bias tracking, and its operation is successfully verified through measurement under intentional temperature perturbation.

I. Introduction

Silicon photonics leverages mature CMOS processes to provide high-density integration of Si photonic integrated circuits (PICs). The explosive demand for high data throughput in AI and HPC has positioned Si PICs as a key solution. Particularly in the form of co-packaged optics (CPO), Si PICs are expected to satisfy the requirements of high throughput, a compact form factor, and low power consumption. Among various components, the Si micro-ring modulator (MRM) is a vital building block due to its ultra-compact footprint and high bandwidth. The present applications of Si MRMs for AI compute interconnects are based on IM/DD [1], but there is a growing interest in using Si MRMs for coherent applications, which can further enhance spectral efficiency and data throughput while maintaining a compact device and low-power consumption. Although high-performance Si MRM-based coherent transmitters, including ring-assisted Mach-Zehnder structures [2], [3], [4], [5] have been reported, there remains a challenge of stabilizing MRMs against temperature fluctuation [6] and process variation [7], which can greatly degrade the constellation and the bit-error rate (BER).

In this work, we propose and demonstrate a new temperature stabilization technique with which a Si MRM-based coherent transmitter can successfully perform 25-Gbaud QPSK operation.

II. Device and Temperature Stabilization Technique

The coherent transmitter used for our demonstration is based on a ring-assisted Mach-Zehnder interferometer (RaMZI) structure [Fig. 1(a)]. The RaMZI integrates two single MRMs within the MZI arms to modulate the in-phase (I) and quadrature (Q) components of the QPSK signal. The device was fabricated with IHP's 0.25-µm Si photonic BiCMOS process [8]. Heater voltages V_{H1} and V_{H2} control the resonance of MRMs, while V_P applied to the phase shifters in the MZI adjusts the optical phase difference of the MZI for quadrature alignment. Although each arm is equipped with a phase shifter, only V_P was utilized since the optical phase is relative.

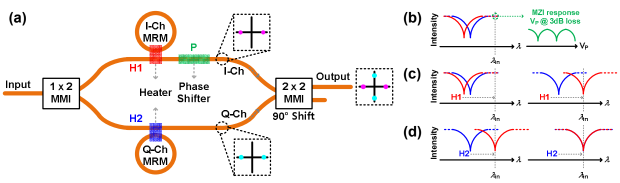

Fig. 1(a) Schematic of coherent QPSK IQ modulator having ring-assisted Mach-Zehnder interferometer (RaMZI) architecture. Phase I (Initial bias optimization) for (b) V_P, (c) V_{H1} and (d) V_{H2}.

The proposed temperature stabilization technique consists of Phase I and Phase II. Phase I (Initial Bias Optimization) performs a coarse-to-fine scan to establish the starting biases. First, V_P is scanned to identify the maximum P_{out} in the MZI response at λ_{in}, and V_P is maintained at the value providing 3-dB drop from the maximum for P_{out} to ensure quadrature alignment [Fig. 1(b)]. Subsequently, V_{H1} and V_{H2} are swept to determine the resonance matching conditions for λ_{in}, which correspond to the points of minimum P_{out}, as shown in Fig. 1(c) and (d). To mitigate thermal crosstalk between the integrated heaters, these processes are repeated with fine steps, ensuring precise alignment for operation.

Phase II (Real-time Bias Tracking) maintains the optimal points against ambient temperature drifts. The tracking logic adopts a recursive approach, using the initial set-points from Phase I under the assumption that the bias deviations between successive iterations remain minimal. During the tracking process, small dither signals are applied to V_P, V_{H1} and V_{H2} sequentially, and the resulting magnitude of fluctuations in P_{out} are monitored. To avoid impractical recalibration during real-time operation at λ_{in}, V_P is updated to track the P_{out} value from the previous iteration rather than relying on a fixed target or re-scanning for the full MZI response. By adjusting V_{H1}, V_{H2} and V_P based on the monitored P_{out} variations, Phase II ensures the RaMZI remains at its optimal operating point concurrently.

III. Measurements

Fig. 2(a) illustrates the measurement setup used for the verification of the proposed temperature stabilization technique. An optical signal from a tunable laser is divided by a 50:50 coupler and supplied to the DUT and the local oscillator (LO) port of a commercial coherent receiver (CoRx) for homodyne reception. A polarization controller (PC) is utilized to align the input state of polarization. The output of the RaMZI is divided by a 10:90 splitter where 10% of P_{out} is monitored as a feedback parameter by an optical power meter, and 90% is amplified by an erbium-doped fiber amplifier (EDFA) and filtered by a tunable optical bandpass filter (OBPF).

An arbitrary waveform generator (AWG) with a sampling rate of 25 Gs/s and an analog bandwidth of 13.5 GHz supplies 25-Gbaud non-return-to-zero (NRZ) signals to the DUT. V_{H1}, V_{H2} and V_P from power supply are utilized as control parameters for either scanning (Phase I) or dithering (Phase II). The stabilization technique is implemented in a Python using the threading package to enable concurrent and independent execution without timing collisions. To verify the stabilization performance, the output waveform is intermittently captured by a real-time oscilloscope (RTO) for off-line DSPs.

For BPSK operation, the V_π, insertion loss, and 3-dB bandwidth of a single MRM at λ_{in} are 5.7 V_{pp}, 10.0 dB, and 18.5 GHz, respectively. To cover the free-spectral range (FSR) of the MRMs (6.24 nm), 91.4 mW of heater power is required, and 57.9 mW is consumed by the phase shifter to compensate for the 2π phase mismatch of the MZI. Further details on the device performance as a coherent transmitter can be found in [3] and [4].

Fig. 2(b) illustrates Phase I where V_P is biased at the 3-dB drop point, and V_{H1} and V_{H2} are set to the resonance notches. After Phase I, the RaMZI is aligned for QPSK operation, resulting in the constellation shown in Fig. 2(c). A bandwidth limitation is observed in the constellation due to the limited sampling rate and analog bandwidth of the AWG. For the verification of Phase II, the ambient temperature of the DUT is intentionally perturbed using a temperature-controlled stage. A sinusoidal temperature swing of 5°C peak-to-peak around 30°C is applied over a duration of 1800 seconds. During the perturbation, the bias tracking loop adjusts V_{H1}, V_{H2} and V_P based on the monitored P_{out}, as shown in Fig. 2(d). The resulting BER values in Fig. 2(e) confirm that the temperature stabilization technique maintains the signal quality below the 7% HD-FEC limit (3.8×10^{-3}). The cumulated constellations without and with Phase II are recovered and shown as in Fig. 2(f) and (g), respectively. The results verify the effectiveness of the proposed temperature stabilization technique for Si MRM-based coherent transmitters.

IV. Conclusion

We successfully demonstrated a temperature stabilization technique for a RaMZI-based Si MRM coherent QPSK transmitter. The technique maintained stable 25-Gbaud QPSK operation under a 5°C temperature swing, keeping the BER within the 7% HD-FEC limit. While verified in a Python environment, future work will focus on board- and circuit-level implementations for practical applications.

References

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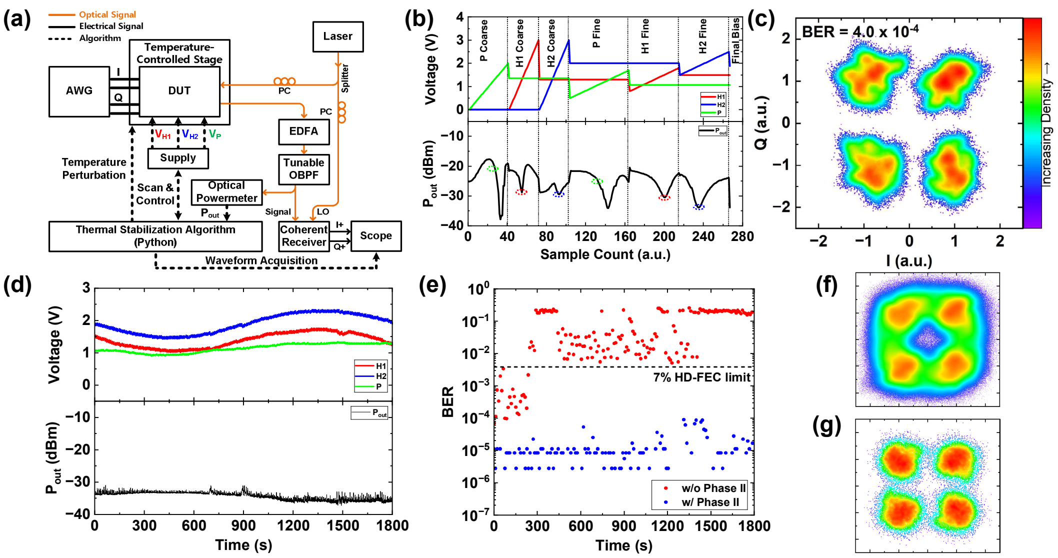

Fig. 2(a) Measurement setup for the proposed stabilization technique. (b) Recorded values of biases and P_{out} during Phase I, (c) resulting constellation of Phase I for 25-Gbaud QPSK signal. (d) Recorded values of biases and P_{out} during Phase II, (e) resulting value of BER in cases of without and with Phase II. Resulting constellation for 25-Gbaud QPSK signals (f) without Phase II, (g) with Phase II.