Precise Phase Measurement with Weak Value Amplification on Integrated Photonic Chip

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Primary CNF Tools Used: Low pressure chemical vapor deposition (LPCVD), plasma-enhanced chemical vapor deposition (PECVD), JEOL 9500 e-beam lithography, ASML stepper, Oxford 100 inductively coupled plasma reactive ion etching (ICP-RIE), AJA sputter deposition

Abstract:

We show, for the first time, phase measurement with weak value amplification on an integrated photonic chip. We demonstrate 9 dB improvement of signal over an on-chip Mach-Zehnder interferometer with equal amount of detected optical power.

Summary of Research:

Weak value amplification has shown the ability to make sensitive measurements with a small portion of the light signal, including beam deflection measurement of 400 frad with 63 μW out of 3.5 mW light power [1], frequency sensitivity of 129 kHz/√Hz with 85 μW out of 2 mW [2] and temperature sensor with 4-fold enhancement [3]. By introducing a perturbation and post-selection of the light, weak value can amplify the interferometric signal without amplifying the noise, resulting in a higher signal-to-noise ratio (SNR). Therefore, in a detector saturation limited system, weak value amplification can further increase the SNR. However, tabletop setups are space consuming and vulnerable to environmental changes. By taking this technique to the integrated photonics regime, we can largely improve its robustness and compactness, making it a good candidate for precision metrology.

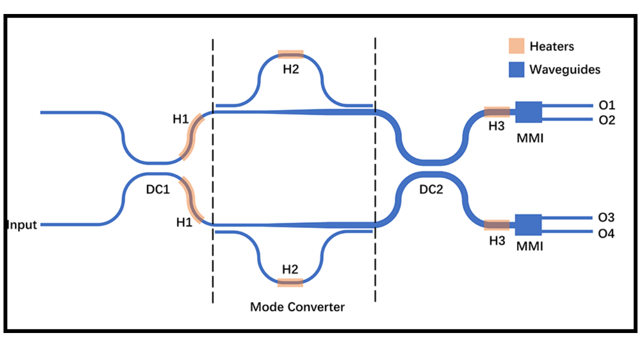

Figure 1: Layout of the device with heaters (not to scale). DC: directional coupler; H: heater; MMI: multi-mode interferometer; O: output.

We used an integrated Mach-Zehnder interferometer (MZI) followed by a multi-mode interference waveguide (MMI) (Figure 1) to achieve inverse weak value measurement. For traditional weak value amplification in optical interferometers, a propagation phase shift between the two paths is introduced to amplify spatial phase front tilt signal introduced by a tilted mirror. However, in integrated photonics, sensing is usually achieved with propagation phase. Therefore, we apply “inverse” weak value amplification (IWVA), which uses spatial phase front tilt to amplify propagation phase signal. To introduce a spatial phase tilt in a waveguide, we designed the mode converter in Figure 1 to couple a small part of the light from TE_0 mode to TE_1. This is based on that the Hermite-Gaussian (HG) expansion of free space IWVA output beam is mainly a combination of HG_0 and HG_1 modes [4]. Since eigenmodes of a waveguide are similar to Hermite-Gaussian modes, we applied the theory on waveguide eigenmodes TE_0 and TE_1.

We design a multimode coupler to couple light from fundamental mode to higher order mode. As shown in Figure 1 (between dashed lines), the straight branch is a single mode waveguide which transits to a multimode waveguide through an adiabatic taper. Therefore, TE_0 mode in the lower waveguide stays in TE_0 mode. The bending branch couples a slight portion of light from TE_0 in lower waveguide. Then it couples back into the lower waveguide, but to TE_1 mode, since the TE_1 mode supported by the multimode waveguide is designed to be phase matched with TE_0 in the bending branch.

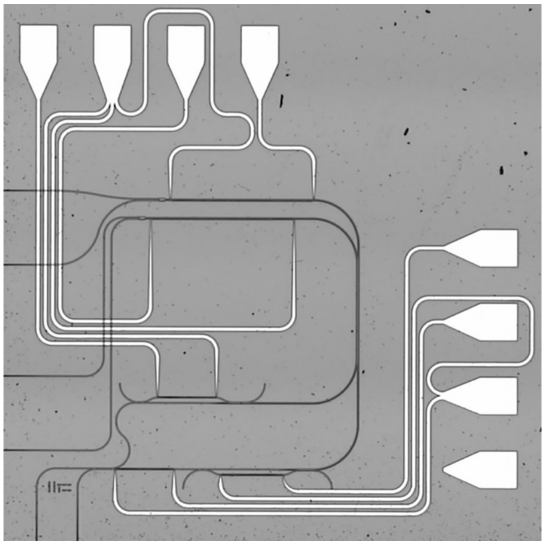

Figure 2: Microscope capture of the device. The device is wrapped around to reduce footprint.

To readout the phase shift introduced by heater 1 in Figure 1, which translates to measuring the ratio of TE_0 and TE_1 modes, we design a multimode interferometer (MMI). We used an MMI as simulation shows that its output power is dependent on the ratio of the input TE_0 and TE_1 modes.

We then fabricated the device with CMOS compatible process (Figure 2). The fabrication started with a 4-inch silicon wafer with 4 μm of thermal grown silicon dioxide. We deposited a layer of 289 nm silicon nitride with low pressure chemical vapor deposition (LPCVD). Then we used e-beam lithography to pattern the waveguides and etched the silicon nitride with inductively coupled plasma reactive ion etching (ICP-RIE). We deposited 2.6 μm of silicon dioxide with plasma enhanced chemical vapor deposition (PECVD).

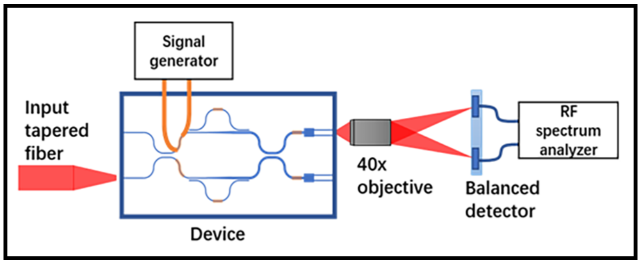

Figure 3: Illustration of testing setup.

Finally, we sputtered 100 nm of platinum, patterned with deep UV lithography, and used lift-off method to form the heaters.

We compare our weak value device with a standard on-chip MZI with same footprint working in quadrature (Figure 3). We launch 1 mW of laser power at 1570 nm with a tapered optical fiber. The phase signal is introduced by applying a modulated 1V, 10 kHz sinusoid voltage to heater 1.

The outputs of the waveguides are imaged onto a balanced detector, and we measure the signal on an RF spectrum analyzer.

We demonstrate 9±1.9 dB signal improvement over the regular MZI in the weak value device with equal amount of detected optical power. When detected powers are 14 μW, weak value device has a signal of 66.17 dBm, while the regular MZI shows 75.33 dBm. For the regular MZI to also show a signal of 66.17 dBm, it requires a higher detected power of 40.5 μW.

Conclusions and Future Steps:

In conclusion, we have shown that on-chip weak value device is a good candidate for phase related metrology, including temperature drift and frequency shift. As it provides higher signal with same amount of optical power, it can monitor the optical signal in a system without consuming a large portion of the light. On the other hand, in a detector saturation limited system, weak value device is able to further increase the signal.

References:

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