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High-performance, low-cost optical coherence tomography (OCT) digital Fourier Transform (dFT) spectrometer on a silicon photonic platform

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Abstract:
Optical Coherence Tomography (OCT) is limited by cost and size. We've developed a compact, chip-integrated OCT system with a spectrometer, delay line, and beam scanning. It features a 1310nm central wavelength, 100nm bandwidth, 0.0977nm resolution, 108.45dB sensitivity, and 8.8µm axial resolution.

1. Background

Unlike conventional spectral-domain (SD) OCT systems which involve a spectrometer assembled from bulky optics, here we demonstrate an on-chip Spectrometer architecture on a Silicon chip utilizing the digital Fourier Transform (dFT) spectrometer. Our approach eliminates complex assembly and alignment steps, leverages standard silicon CMOS foundry infrastructure to facilitate scalable low-cost manufacturing, and deploys an innovative optical design to achieve high performance. These innovations uniquely define our technology's value proposition – offering a high-performance, shoe-box-sized imaging platform with > 10x lower cost to significantly expand the market of OCT, addressing the rapidly increasing demands from tissue diagnostics. We demonstrate a silicon-based digital Fourier Transform (dFT) spectrometer [1] that offers significant performance and cost benefits. This miniaturized spectrometer simplifies the architecture, improves resolution, and enhances the signal-to-noise ratio, making it a more efficient alternative to traditional spectrometers.

2. Methods

2.1 Spectrometer Design & Simulation

The dFT spectrometer design is based on a 5-stage design (j = 10) with a target center wavelength of 1310 nm and a 100 nm bandwidth. It includes 1024 spectral channels with a spectral resolution of 0.0977 nm and a total on-chip insertion loss of less than 7 dB. This design can provide up to 108.45 dB sensitivity and support an axial resolution of up to 8.8 µm. We simulated a complete spectrometer model encompassing: full-vectorial FDTD simulations of components; S-matrix model at the circuit level, based on FDTD component simulation results with Lumerical software and AIM Photonics Process Design Kit (PDK) component lumped models; and statistical analysis accounting for component performance changes due to fabrication variations. The main piece of dFT spectrometer is a Mach-Zehnder interferometer (MZI) that utilizes cascading optical switches to make a tunable interferometer. The repeating stage design of the dFT consists of an optical switch, a pair of waveguides, and a 2x2 power coupler. The 2x2 coupling elements were custom-designed due to lack of availability within the standard foundry PDK components. We designed an adiabatic coupler for the power splitting component using a step-wise segmented design approach using a combination of ANSYS Lumerical FDTD and EME to optimize the various design parameters. The step-wise approach was inspired by previous work by Wang et al.[2], which allows for improved design efficiency and smaller device footprint, which is useful given the high cost of silicon wafer space. We divided the adiabatic coupler into four regions and optimized each individually. The final device design achieves nearly ideal 50% transmission through each output arm of the adiabatic coupler.

2.2 Mask Layout and Fabrication Tapeout

The mask design for the dFT design was created with a modular-designed Python script using the IPKISS Photonics Design Platform. The IPKISS platform enables easy integration of the custom-designed adiabatic coupler with AIM Photonics foundry components, and design rule checks. Once the layout was completed, the design was written to a GDS file and the Design Rule Check (DRC) was performed to ensure the file met the

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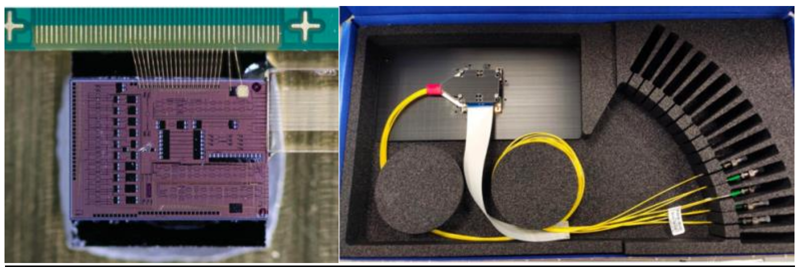
foundry specifications. The design was submitted for fabrication through the multi-project wafer (MPW) shuttle of the AIM Photonics Foundry. The fabrication process features attenuation less than .25 and .10 dB/cm for 220nm silicon, in addition to around 1dB/facet edge coupler for both transverse electric (TE) and transverse magnetic (TM) polarization on 300mm silicon on insulator (SOI) wafers.

2.3 Device Packaging

The devices were assembled and packaged into two prototypes by PHIX. The company provided the housing with electrical connections, optical interfaces, and thermal management. The chips were attached to a Silicon sub-mount and the electrical interfaces were attached with a custom PCB with 20 DC connectors.

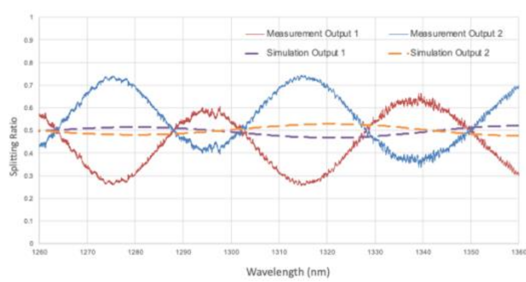
Fig 1. Left: Electrical connections and optical fibers attached to OCT device. Right: Photonic packaged assembly



3. Results

The complexity of the dFT devices warrants that each individual component needs to be tested to characterize the full device. The adiabatic couplers were tested to confirm the splitting ratio, the photodetectors were characterized by measuring the wavelength-dependent responsivity spectra and polarity, the heaters were tested both for their consistency of resistance across individual heaters (PV curves), and voltages required to switch through the permutations. We used a Santec tunable semiconductor laser with 1260-1360nm wavelength operation and 0.005nm wavelength step-size. We swept the full bandwidth of the laser and measured the adiabatic coupler performance, and compared it to the simulation results.

Fig 2. Comparison of measured adiabatic coupler performance with simulation results.



The last step of the spectrometer testing is to step through the permutations of the bandwidth and wavelength step, which is currently in the process with the recently determined heater voltages.

4. Conclusion & Future World

Here we demonstrate a dFT spectrometer that will be integrated into an OCT imaging system. Our next direction is to finish calibration of the spectrometer and integrate the spectrometer into a pre-built OCT imaging system to image tissue phantom specimens.

5. References

[1] D. M. Kita *et al.*, "High-performance and scalable on-chip digital Fourier transform spectroscopy," *Nat. Commun.*, vol. 9, no. 1, p. 4405, 2018, doi: 10.1038/s41467-018-06773-2.

[2] Y. Wang *et al.*, "Polarization-Independent Mode-Evolution-Based Coupler for the Silicon-on-Insulator Platform," *IEEE Photonics J.*, vol. 10, no. 3, pp. 1–10, 2018, doi: 10.1109/JPHOT.2018.2835767.