Ultra-high resolution and broadband chip-scale speckle enhanced Fourier-transform spectrometer

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Recent advancements in silicon photonics are enabling the development of chip-scale photonics devices for sensing and signal processing applications. Here we report on a novel passive, chip-scale, hybrid speckle-enhanced discrete Fourier transform device that exhibits a two order-of-magnitude improvement in finesse (bandwidth/resolution) over the current state-of-the art chip-scale waveguide speckle and Fourier transform spectrometers reported in the literature. In our proof-of-principle device, we demonstrated a spectral resolution of 140 MHz with 12-nm bandwidth for a finesse of $10^4$ that can operate over a range of 1500-1600 nm. This chip-scale spectrometer structure implements a typical spatial heterodyne discrete Fourier transform waveguide interferometer network that is enhanced by speckle generated from the wafer substrate. This latter effect, which is extremely simple to invoke, superimposes the high wavelength resolution intrinsic to speckle generated from high NA waveguide with a more broadband but lower resolution DFT modality of the overarching waveguide structure. This hybrid approach signifies a new pathway for realizing chip-scale spectrometers capable of ultra-high resolution and broadband performance.

I. INTRODUCTION

Chip-scale optical spectrometers are envisioned as key elements for next generation remote sensing systems and precision on-chip wavelength monitoring. A primary example is the development of optical devices for detection of chemical species on remote platform[1–6]. For space applications, a compact, high-resolution, and alignment free spectrometer with no moving parts or exposed surfaces is highly desirable. Recent advances in silicon photonics are enabling the fabrication of such devices using CMOS compatible commercial foundries and offer significant size, weight, and power (SWAP) along with cost advantages over traditional spectrometers.

Silicon-on-insulator (SOI) discrete Fourier transform (DFT) [7–11] and multimode waveguide (MMW) based speckle spectrometers [12–16] are two promising architectures. Despite their versatile performance, both technologies suffer from a bandwidth-resolution tradeoff [8–10, 17]. For example, the spectral resolution ($\delta\lambda$) of a DFT spectrometer is inversely proportional to the maximum path-length difference ($\Delta L_{\text{max}}$) of the interferometers used and the bandwidth ($\Delta\lambda$) and the finesse ($\Delta\lambda/\delta\lambda = N/2$) are set by the total number of interferometers ($N$). Similarly, the spectral resolution of a speckle spectrometer derived from a MMW is inversely proportional to its length and its bandwidth is given by $\Delta\lambda \sim (N_m - 1)\delta\lambda$, where the finesse is set by the number of distinct speckle modes ($N_m$) available for the measurement [17]. As constructing a single spectrometer with a large finesse will require fabricating thousands of interferometers or spectral multiplexing or other exotic configurations, the fineses of the current state-of-the art chip-scale DFT and MMW speckle devices are limited to a few hundred [7,10] thus a larger finesse device would be highly desirable.

In this Article, we report on a first demonstration of a speckle-enhanced DFT (SDFT) chip-scale spectrometer which combines both modalities on a single chip to achieve a finesse that exceeds the current state-of-the-art performance of either chip-scale spectrometer types by two orders of magnitude. This combination of DFT and speckle modalities yields a device with the broader bandwidth characteristics of the DFT and the higher resolution characteristics of the MMW without increasing the number of structures or increasing the size of the device.

II. SPECTROMETER DESIGN AND OPERATION

A. Device Layout

Traditional Fourier-transform spectrometers incorporate an unbalanced Michelson interferometer where light intensity is monitored at an output port while scanning the relative path length difference between the two arms. By taking the Fourier transformation of the recorded intensity, the unknown input spectrum is reconstructed. An analogous discrete Fourier transform spectrometer, also referred to as spatial heterodyne FT spectrometer, implements an array of unbalanced Mach-Zehnder interferometers with predefined relative path length differences [7,10]. In this manner, no active scanning mechanism or alignment procedures are required, making them more robust. Data throughput is potentially improved due to parallel processing needed for this approach.

The DFT functionality of our SDFT spectrometer is implemented using such spatial heterodyne interferometers on a SOI platform. The layout for the SDFT spec-
trometers was developed using an open-source PDK developed by SI-EPIC [18] and fabricated using a CMOS compatible commercial foundry (Applied Nanotools). The Mach-Zehnder interferometers (MZIs) were fabricated using single-etch electron-beam lithography on a 220 nm thick layer of silicon. Arrays of 64 and 128 MZIs were built using 500 nm wide single-mode waveguides (that sustain both $TE_{00}$ and $TM_{00}$ modes) with a 50-$\mu$m stepwise incremental pathlength differences. A schematic diagram of the SDFT spectrometer along with a microscope image of the fabricated device are shown in Fig. 1. The DFT functionality used in this study is enclosed by the red box which consists of 64 MZIs.

The MZIs in the array are optically coupled via a cascaded network of 3 dB Y-splitters. The output of the MZIs are terminated at the end of the chip where the light emission is imaged on a camera array. A 2 $\mu$m thick oxide layer is grown on top of the interferometers for protection and reduce thermal sensitivity. The optical input waveguide is off-centered from the field of view of the camera imaging the output waveguides to minimize any leaked light propagating on top of the device that otherwise would saturate the detector arrays.

The speckle functionality is derived from the 8.5 mm long 675 $\mu$m thick silicon handler wafer which behaves as a strongly guiding planar MMW that sits below the DFT waveguides. The SOI waveguide sustains several hundred thousand optical modes which yields highly developed speckle at the output of the chip.

Light is coupled to the MZIs and the MMW through one end of the chip using a high-NA single-mode fiber (NA=0.41) and the output of the chip is imaged using a 4x microscope objective and a high-speed InGaAs camera array (GoodRich SU640KTS). Trenches etched along the perimeter of the chip along with inverse taper structures at the output of the waveguides facilitate coupling of the input light into the chip [19, 20]. Due to a slight mode mismatch between the fiber and the tapered waveguide structure, a fraction of the input light is leaked into the substrate MMW. This results in the simultaneous propagation of the optical beam through both the MZIs (DFT spectrometer) and the MMW (Speckle spectrometer), thus forming a hybrid SDFT spectrometer.

### B. Theory of Operation

The electric field output of the optical modes propagated through an ideal substrate waveguide with length $L$ can be written as [13]

$$E_{\text{speckle}}(x, y, L) = \sum_m C_m \psi_m(x, y, \lambda) \exp[-i(\beta_m(\lambda)L - \omega t + \phi_m)]$$

(1)

where $\psi_m$ is the spatial profile of the $m$th mode that has initial amplitude $C_m$ and phase $\phi_m$ with propagation constant $\beta_m$ and is measured at $(x, y)$ coordinate at the output facet of the waveguide. A large width slab waveguide sustains several thousand optical modes and the interference between those modes results in a speckle pattern. In addition, the propagation constant is wavelength dependent and as a consequence, any change in the input wavelength results in the modification in the output interference pattern that generates a unique wavelength dependent fingerprint. Similarly, the electric field of the MZI array output is

$$E_{\text{MZI}}(x, y, \lambda, L) = C \sum_{n=1}^{N} \psi_n(x, y, \lambda) \exp[i\phi](1 + \exp[-i\beta \Delta L_n])$$

(2)

where $\psi_n(x, y, \lambda)$ is the spatial mode distribution at the input.
output of the waveguide and $\Delta L_n$ is the relative path-length difference of nth MZI.

The total output power recorded by a camera at the output facet of the chip can be calculated by taking the modulus square of the sum of the output electric fields from both the MMW and MZI array. The SDFT device can be effectively treated as a transformation operator ($A_{SDFT}(x, y, \lambda)$) that maps the input spectral information ($S(\lambda)$) to the output spatial dependent intensity pattern,

$$P_{\text{out}}(x, y, \lambda) = A_{SDFT}(x, y, \lambda).S(\lambda)$$  \hspace{1cm} (3)

where the transformation operator is the sum of wavelength-spatial responses from the component MZI arrays and the MMW substrate (speckle), and any cross term that could arise from the interference between modes from both components. An exact first principles calculation of such transformation matrix is a complicated task; however, one can experimentally measure the wavelength-and spatial-dependent transmission matrix ($A_{SDFT}$), or calibration matrix, by tuning a narrow bandwidth single-frequency laser and recording the intensity pattern with a camera.

III. RESULTS: DEVICE CHARACTERIZATION

A. Calibration

Figure 2(a) is an experimentally recorded image of the output of the SDFT chip. The dashed white box represents a SDFT region consisting of both MZI and speckle output and the red box consists of speckle-only contribution from the MMW. The intensity distribution of the output of the MMW recorded by the camera is plotted in Fig. 2(b) along with a negative-exponential decay fit to it, where x-axis is the intensity normalized by the mean and y-axis is its distribution. This negative-exponential decay in the intensity pattern is a characteristic of fully developed speckle resulting from a large number of modes interference \cite{21}.

The region of the chip corresponding to the SDFT and speckle-only output are summed column-wise to generate a 1D pixel array of the calibration matrix at a discrete wavelength step for the corresponding device. Figure 2(c) is an example SDFT calibration matrix recorded from the output of a 64-element SDFT chip over a 100 nm spectral window generated by scanning a narrow band continuous-wave (CW) laser. For a wavelength dependent 2D intensity output of the SDFT device see Supplementary 2. Figure 2(d) shows the transmission profile of two MZIs with $\Delta L = 0$ $\mu$m and 50 $\mu$m recorded over a 100 nm spectral window and consists of intensities from both MZIs and the MMW, where the speckle corrupts the MZIs transmission as a high-frequency noise, forming a unique wavelength dependent fingerprint for the combined SDFT spectrometer within the bandwidth of the DFT spectrometer. When reconstructing a broad spectrum using such a calibration matrix, the speckle contribution of the MMW is minimal–as the algorithm averages it out as noise–thus allowing one to accurately reconstruct a broad spectrum. On the other hand, when the reconstruction is performed within a smaller spectral window within the resolution limit of the DFT-only device, the output of the MZIs acts as a slowly varying DC-like offset, while the contribution of the speckle pattern on the calibration matrix becomes significant. This behavior allows the algorithm to robustly reconstruct both a broad and high-resolution spectrum and circumvent the resolution-bandwidth tradeoff.

With the knowledge of such a calibration matrix, the spectral content of an unknown light input to the spectrometer can be reconstructed by solving $S = A^+P_{\text{out}}$, where $A^+$ is the pseudoinverse of matrix A. If the number of measurements is smaller than the wavelength points to be reconstructed, the system of linear equations is under-constrained. Such constrained linear equations can be solved using least square minimization \cite{22}, such as the elastic-net regularization technique \cite{11}, such as

$$S(\lambda) \equiv \arg \min_{S,S>0} \left\{ ||P_{\text{out}} - A.S||^2 + l_1||S||_1 + l_2||S||^2_2 \right\}$$ \hspace{1cm} (4)

where $l_1$ and $l_2$ are regularization hyperparameters that are appropriately selected depending on the density of the reconstructed spectrum. $l_2 = 0$ gives a well

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FIG. 2. (a) Recorded output image of a 64 MZI SDFT chip for monochromatic input light at 1550 nm. The dashed white box represents a SDFT region consisting of both MZI and speckle output and the red box consists of speckle-only output from the MMW. (b) Intensity distribution recorded at the speckle-only region of the chip fitted with a negative exponential decay shows a fully developed speckle pattern arising from the multimode interference of the beam propagating through the substrate waveguide \cite{21}. (c) Wavelength dependent transmission matrix recorded from the output of the spectrometer recorded over 100 nm spectral window. (d) Transmission profile of a $\Delta L = 0$ $\mu$m and 50 $\mu$m MZIs each recorded from a single pixel of the camera by tuning wavelength over 100 nm spectral window. The output intensity has the speckle contribution overlapped to it.
known lasso regularization used for compressive sensing on sparse signal, and \( l_1 = 0 \) gives a 2-norm Tikhonov regularization (or ridge regression) appropriate for reconstructing a dense signal. Such regularization technique allows a robust reconstruction of the input signal over noisy or unconstrained data.

**B. Statistical Analysis of the Device**

The performance of the SDFT spectrometers and the information content available for reconstructing the spectrum can be studied by performing statistical and linear algebra analyses of the images recorded at the output of the chip. A 1D intensity values recorded from the SDFT region and speckle-only region are plotted in Fig. 3 (a) and (b). In this example, the relative contribution of the speckle on the MZI array is \( \sim 15\% \) in this measurement. The speckle contribution to the SDFT device can be increased by intentionally misaligning the input fiber such that more light passes through the substrate. The black curve shows the contribution of the background and detector noise.

The spectral resolution of the device is set by the wavelength correlation of the output intensity pattern and is given by [13, 23],

\[
C(\Delta \lambda, x) = \frac{\langle I(\lambda, x)I(\lambda + \Delta \lambda, x) \rangle}{\langle I(\lambda, x) \rangle \langle I(\lambda + \Delta \lambda, x) \rangle} - 1, \tag{5}
\]

where \( \langle I(\lambda, x) \rangle \) is the intensity recorded by the camera at position \( x \) for an input optical wavelength \( \lambda \) averaged over all spatial positions. The spectral resolution (\( \Delta \lambda \)) of the device is set by the correlation width at which the speckle correlation drops to half.

Figure 3 (c) is the normalized wavelength correlation of the SDFT spectrometer measured by averaging over multiple pixels recorded at the output of the chip. The data shows two distinct features, where a rapid intensity de-correlation is overlaid on top of a slow de-correlation. The narrow peak circled around the plot is due to the highly de-correlated speckle pattern and the slowly varying feature is due to the DFT spectrometer. (d) Averaged intensity correlation data generated from a separate high-resolution RF-scan measured by stepping the RF frequency with 10 MHz step. The decorrelation width of the SDFT spectrometer is 140 MHz, which sets the true resolution of the device. (e-f) Comparison of the singular values for MZI-only (theory), speckle-only (exp), SDFT spectrometer (exp) and the background noise (exp). The comparison is shown for (e) coarse scan over a broad wavelength window and (f) high-resolution fine scan over a small bandwidth.

Further insights on the information content carried by the SDFT matrix can be gained by performing singular value decomposition (SVD) analysis of the calibration matrix [15, 22, 24]. A rectangular calibration matrix \( \mathbf{A}_{SDFT} \in \mathbb{R}^{n \times m} \) built by scanning \( m \) wavelength steps and summing 2D camera pixels column wise to generate \( n \) measurements can be decomposed as \( \mathbf{A} = U \Sigma V^T \). \( U \) and \( V \) are left- and right-eigenbasis of the matrix and \( \Sigma \) is an \( m \times n \) diagonal matrix containing \( r \) non-zero singular values, where \( r \) is the rank of the calibration matrix and corresponds to the uncorrelated eigenvectors for sig-
nal reconstruction. Singular values are square roots of the eigenvalues of the $A^T_{SDFT}A_{SDFT}$ matrix and are arranged in descending order. The larger singular values capture most of the signal information contained in the calibration matrix and the values closer to zero simply add noise to the system.

To perform comparative studies between speckle-only, DFT-only, and SDFT spectrometers, we generated calibration matrices for each device by summing rows of pixels from SDFT region and speckle-only region as shown in Fig. 2(a). The calibration matrices are normalized to have a unit Frobenius norm so that the relative magnitude of the singular values can be compared [15]. The DFT-only calibration matrix is numerically simulated [7]. Figure 3(e) is the comparison of singular values for various devices at a wider bandwidth regime (10 nm with 0.01 nm steps). A large number of distinctive eigenfunctions with larger values allows for better signal reconstruction [15, 24, 25]. The SDFT spectrometer consists of 64 large singular values corresponding to the 64 MZI channels that provide coarse resolution and additional $\sim$ 500 smaller eigenvalues corresponding to high-frequency eigenfunctions that provides enhancement in spectral resolution. As the data indicates in Fig. 3(e), the addition of speckle extend the number of eigenvectors available for signal reconstruction (blue curve) for SDFT spectrometer over the rank deficient DFT-only spectrometer (purple curve). The extended singular values are above the background noise level (yellow). This added contribution results in the increase in the resolution of the device over the traditional DFT spectrometer and bandwidth increase over the speckle-only spectrometer [17].

Figure 3(f) is the comparison of singular values calculated from a calibration matrix recorded over a smaller wavelength region (50 pm) but with a finer spectral scan steps (0.08 pm). As can be seen, the speckle calibration matrix has near identical property as the SDFT spectrometer. This is a result of the contribution from MZI array changing very little within such narrow wavelength scan window thus demonstrates that addition of DFT does not degrade the functionality of MMW speckle. This dual feature indicates that combined coarse resolution, higher bandwidth DFT and high resolution, low bandwidth speckle spectrometer enables one to perform both high-resolution and broad-bandwidth spectra reconstruction using a single device. In this study the input signals were reconstructed using 2D camera output projected to form a 1D array of up to 640 elements. However, for a much denser input signal, the entire 2D pixel array from 2(a) ($\sim$ 150 $\times$ 640) can be used, making all 96,000 spectral channels readily available for spectral reconstruction.

In order for the SDFT spectrometer to provide a unique high-resolution fingerprint over a wide wavelength range, the resolution of the MZI needs to be commensurate with the free spectral range of MMW. To achieve both high-resolution and broad-bandwidth reconstruction, first a coarse spectrum limited by the resolution of the DFT can be reconstructed using a larger regularization parameter. Once the coarse spectrum is identified, the high-resolution spectrum can be reconstructed using a subset of the calibration matrix limited within the narrow spectral bandwidth using the above mentioned signal processing techniques. A single high-resolution broad bandwidth calibration matrix and a single measurement is sufficient for signal reconstruction. The bandwidth of this hybrid device is estimated to be $B \sim N/2 \times \Delta \lambda$, where $\Delta \lambda$ is the bandwidth of the speckle spectrometer and $N$ is the number of MZIs.

IV. SPECTRUM RECONSTRUCTION

To demonstrate the functionality of the device, a series of two-tone reconstructions are performed using two monochromatic tunable lasers. Two-tone tests were performed by simultaneously sending one fixed and one tunable laser through the spectrometer. A series of intensity patterns at the output of the SDFT region were recorded while scanning the relative detuning between the two input lasers. The laser is scanned at 1 pm step from 1555 nm to 1557 nm. Using the calibration matrix and the recorded output intensity pattern, we are able to reconstruct the dual wavelength input spectrum as the tunable laser is stepped across the entire range. A series of reconstructed spectra using the intensity pattern recorded from the SDFT device is plotted in Fig. 4(a) where the
y-axis corresponds to collects at different wavelengths of the tunable laser. The vertical line represents the fixed wavelength laser, where the diagonal line represents the tunable laser. The data is reconstructed using $l_2$ regularization with a small regularization parameter, where the weight of the regularization is directly related to the reconstruction resolution [20]. See Supplementary figure for comparison of the reconstruction using other regularization techniques. A detailed analysis on the signal reconstruction technique and the effect of regularization on computational spectrometers are given in Refs. [11, 24].

To compare the performance of the device, we theoretically simulated a calibration matrix and intensity pattern generated by the DFT-only spectrometer with comparable MZI parameters. The reconstructed spectrum is plotted in Fig. 4 (b) for comparison. As the figure demonstrates, the SDFT spectrometer far outperforms the resolving capacity of the DFT-only spectrometers and is able to resolve two closely spaced spectrum.

To experimentally demonstrate the spectral range of the SDFT device, we repeated the two-tone experiment over 10 and 30 nm window. The calibration matrix of the SDFT device is recorded by summing the pixel arrays from the dashed white region in Fig. 2 (a), where the output is an overlap of MZIs and speckle modes. To compare the performance of the device with the speckle-only spectrometer, speckle calibration matrix is generated by recording pixels below the MZIs array (dashed red region in Fig. 2 (a)) where the multimode speckle data has minimal to no contribution from the MZI output. The two-tone reconstruction experiment is repeated for both systems, where the data is acquired simultaneously within the same shot of the measurement. The reconstructed spectrum using the SDFT and speckle-only spectrometers are plotted in Fig. 3 (a) and (b). As can be seen, the SDFT device is able to reconstruct the spectrum for a larger bandwidth region, whereas the speckle-only reconstructs multiple false spectral spectra in addition to the true spectra. This is due to the limited number of unique speckle fingerprint available as the input spectral window is increased. A detailed theoretical comparison on the performance of the two devices is given in Supplementary Section 7.

To display the spectral range of the SDFT, we collect data over a 30 nm sweep of the tunable laser. As can be seen in Fig. 5 (c), the reconstruction pattern repeats after 12 nm, thus indicating the bandwidth of the device.

The arrows indicate the true spectral location of the input lasers with the enclosed red box consisting of true spectra within the free-spectral range of the DFT spectrometer (12 nm). The measured bandwidth is twice the predicted bandwidth for a DFT spectrometer [9]. This additional enhancement in bandwidth is attributed to the combination of the speckle and the reconstruction algorithm [15].

All the data reported in this Article are taken in an open lab setting without precise temperature stabilization of the chip. The test data is typically taken within 30 minutes of the calibration. The device has been tested over an input power range of 1 to 6 mW. The dynamic range of the reconstructed spectrum is measured to be $\sim 12$ dB, which is limited by the measured signal-to-noise (SNR) of the output intensity and noise induced by system instability. This should be partly mitigated by packaging the device to thermally and mechanically isolate it from external perturbations and measured signal can be increased by coating the unused surfaces of
the chip with high-reflecting mirrors.

Speckle generated by multimode fibers are known to be particularly sensitive to small strain or temperature fluctuations \[13\]. A detail analysis of the effect of temperature drift of such speckle and DFT spectrometers are reported in Refs. \[17, 27, 28\]. The small footprint of the device (\( \sim 1cm^2 \)) with a shorter path length partially mitigates the thermal and stain issues that a multimode fiber speckle spectrometer suffers from. In addition, it has been reported that the speckle patterns generated by input light with wavelength \( \lambda \) at temperature \( T + \delta T \) and by input light at wavelength \( \lambda + \delta \lambda \) at temperature \( T \) are the same \[17\]. Thus any spectral drift due to a small change in temperature can be compensated by a single correction offset in the reconstructed spectrum. Alternatively, the temperature of the spectrometer can be monitored and controlled by fabricating a layer of metallic heater on top of the device.

V. CONCLUSION

In this Article, we demonstrate a novel chip-scale, passive spectrometer that combines a discrete Fourier-transform and a speckle functionality in a single device to significantly increase the finesse over the individual DFT and speckle-only spectrometers. We demonstrate that the device can resolve two laser separated by 3 pm and determine the true resolution of the device to be \( \sim 1 \) ps (140 MHz) using intensity correlation measurement. The device has 12 nm bandwidth within an operational window of 100 nm in the 1500 nm-1600 nm region. The finesse of our device is \( \sim 10,000 \), two orders of magnitude larger than individual DFT or speckle spectrometers \[7, 11, 13, 14\]. To achieve the experimentally demonstrated bandwidth and resolution reported in this Article using a DFT-only spectrometer \[7, 8\] would require 10,000s of MZIs, making it infeasible for a chip-scale device. Even though speckle-based chip-scale spectrometers can achieve such high resolution, they are severely limited to a small operational bandwidth (0.1 nm) \[17\]. The competing technologies involve using two different devices with coarse and fine resolutions \[13\] or using optical switches or spectral multiplexing \[29\] to achieve high-resolution and large-bandwidth reconstruction simultaneously. This significant improvement in the finesse was achieved even though the footprint and bandwidth of our device was not optimized. This device can be trivially extended in the same platform to have \( > 100 \) nm bandwidth centered at \( \sim 1550nm \) by fabricating 128 MZIs with \( \Delta L_{min} \leq 1.9 \mu m \). The operational range of the device is set by the wavelength specifications of the Y-splitter and edge coupler but can be extended to anywhere within the transparency window of silicon. In addition, by using heterostructures of different materials, the design can be extended to operate at a much wider range of wavelengths of interest.

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SUPPLEMENTAL DOCUMENTS

See Supplemental Documents for further details.

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