SPIDER: Next Generation Chip Scale Imaging Sensor

Alan L. Duncan, Richard L. Kendrick, Chad Ogden, Danielle Wuchenich
Lockheed Martin ATC, 3251 Hanover Street, Palo Alto, CA, USA 94304
Samuel T. Thurman
Lockheed Martin Coherent Technologies, 135 S. Taylor Ave., Louisville, CO 80027, USA
S. J. S. B. Yoo, Tiehui Su, Shibnath Pathak, Roberto Proietti
Department of Electrical and Computer Engineering, University of California, Davis, California 95616, USA

AMOS CONFERENCE PAPER

1. ABSTRACT

The LM Advanced Technology Center and UC Davis are developing an Electro-Optical (EO) imaging sensor called SPIDER (Segmented Planar Imaging Detector for Electro-optical Reconnaissance) that provides a 10x to 100x Size, Weight, and Power (SWaP) reduction alternative to the traditional bulky optical telescope and focal plane detector array. The substantial reductions in SWaP will reduce cost and/or provide higher resolution by enabling a larger aperture imager in a constrained volume.

Our SPIDER imager replaces the traditional optical telescope and digital focal plane detector array with a densely packed interferometer array based on emerging photonic integrated circuit (PIC) technologies that samples the object being imaged in the Fourier domain (i.e., spatial frequency domain), and then reconstructs an image. Our approach replaces the large optics and structures required by a conventional telescope with PICs that are accommodated by standard lithographic fabrication techniques (e.g., CMOS fabrication). The standard EO payload integration and test process which involves precision alignment and test of optical components to form a diffraction limited telescope is, therefore, replaced by in-process integration and test as part of the PIC fabrication that substantially reduces associated schedule and cost. This paper provides an overview of performance data on the first generation PIC for SPIDER developed under DARPA SeeMe program funding. We also provide a design description of the SPIDER Zoom imaging sensor and the second generation PIC (high and low resolution versions) currently under development on the DARPA SPIDER Zoom program.

2. SPIDER IMAGER DESIGN

Our SPIDER concept consists of thousands of direct detection white-light interferometers densely packed onto photonic integrated circuits (PICs) to measure the amplitude and phase of the visibility function at spatial frequencies that span the full synthetic aperture. SPIDER samples the object being imaged in the Fourier domain (i.e., spatial frequency domain), and then digitally reconstructs an image. The conventional approach for imaging interferometers requires complex mechanical delay lines to form the interference fringes resulting in designs that are not traceable to more than a few simultaneous spatial frequency measurements. SPIDER achieves simultaneous measurements on many baselines by employing micron scale optical waveguides and nanophotonic structures fabricated on a PIC with micron scale packing density to form the necessary interferometers.

The SPIDER imager samples the object visibility function in a far-field (pupil) plane (i.e., spatial frequency or uv-plane), and then digitally reconstructs an image through an inverse Fourier transform relationship. Fig. 1(a) shows an example SPIDER design consisting of lenslet arrays covered by tube assemblies to control stray light. There are 37 PIC cards beneath the lenslets. The lenslets' spacings and the radial arrangement of the PIC cards uniformly sample the object's two-dimensional Fourier transform. An alternate rectangular geometry is shown in Fig. 1(b). Fig. 1(c) illustrates that the PIC contain various components (delay lines, spectral demultiplexers, phase modulators, beam combiners, and detectors) necessary for making the visibility measurements. The largest lenslet separation (equivalent to the maximum interferometer baseline B_{max}) determines the spatial resolution of the imager. An additional circuit board contains readout and DSP electronics to process the fringe measurements and reconstruct an output image. As illustrated in Fig. 1(c), different waveguides behind each lenslet collect light from different regions of the scene (shown as different colored focusing beams) and light collected for the same field point with different lenslets is combined to create fringes, which are measured with on-chip detectors. In this way, the object complex visibility (amplitude and phase) are recorded for each field point and baseline, and then an image is numerically reconstructed. Fig. 1(d) shows a picture of the fabricated 1st generation SPIDER PIC.

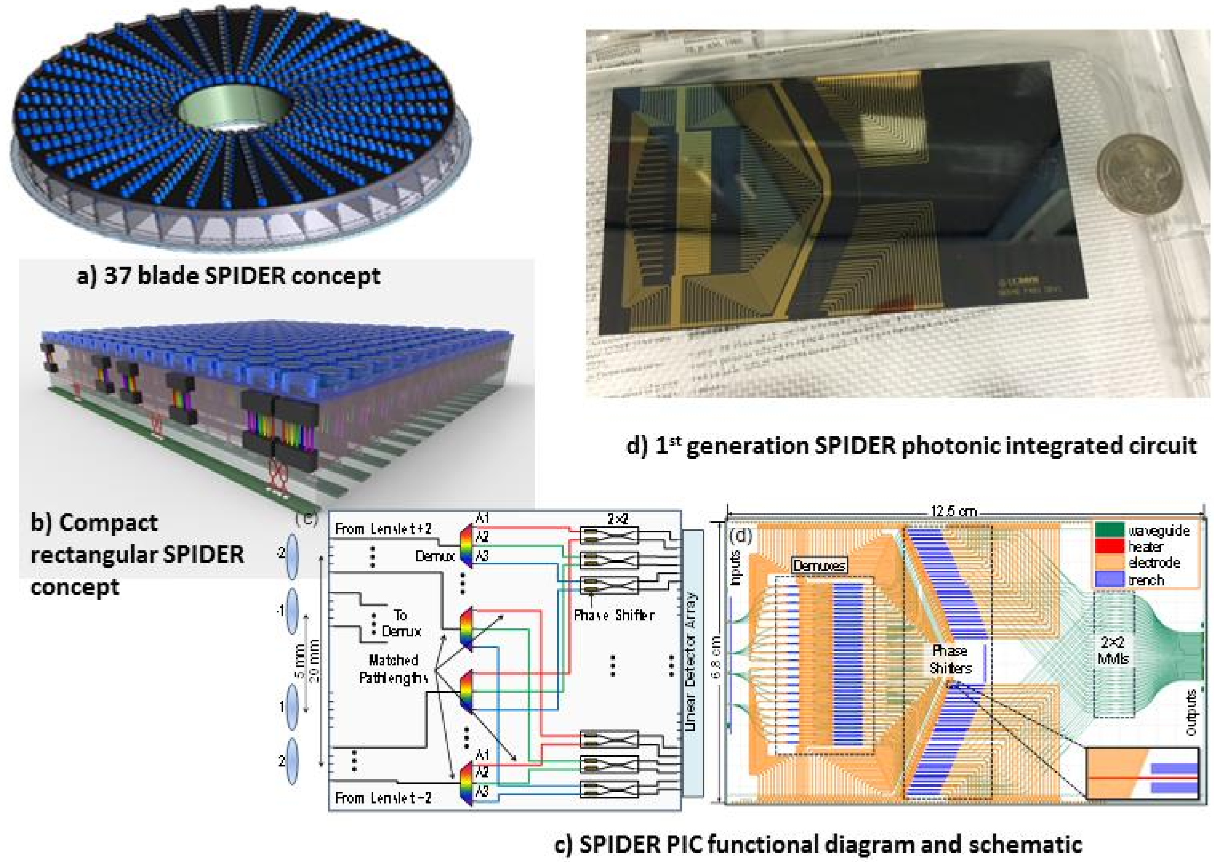

Fig. 1. (a) SPIDER azimuthal blade concept. (b) SPIDER compact rectangular array concept. (c) Schematic view of a single PIC card from the SPIDER imager. (d) Picture of the fabricated PIC.

3. FIRST GENERATION PIC TEST RESULTS

We developed a testbed to demonstrate the SPIDER concept using a 1st generation SPIDER PIC with four lenslets (D = 3 mm, f = 7.5 mm) and two baselines (5 mm and 20 mm). Each lenslet was aligned to couple light into the PIC from a common scene FOV using individual xyz stages. The beam combination output waveguides are butt-coupled to a linear InGaAs detector array for data collection. The printed circuit boards (PCBs) next to the PIC are used for electrical connections to the thermo-optic phase shifters that control the relative phase and to the heaters that fine-tune the spectral demux passbands.

Normalized fringe data for a point source was collected for the short and long interferometer baselines. Sinusoidal curve-fits to the fringe data were performed. Ideally, the normalized fringes for a point source would have amplitudes equal to unity. The estimated fringe visibilities of 0.94 and 0.90 for the short and long baseline, respectively, represent the PIC instrumental visibility.

Fig. 2 shows visibility measurements for an adjustable slit aperture as a function of the slit width. In theory, assuming uniform illumination, the visibility data should trace a sinc curve as the slit width varies. While the absolute value of the measured visibilities is lower than expected, the data follow the expected trend.

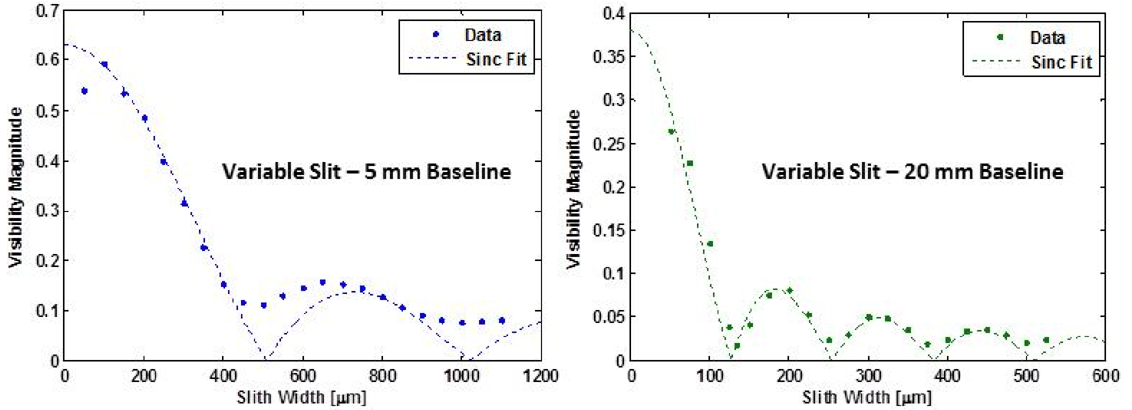

Fig. 2. (a) Measured variable slit visibility for short (5 mm) baselines (source $\Delta\lambda = 2$ nm). (b) Measured variable slit visibility for long (20 mm) baselines (source $\Delta\lambda = 2$ nm).

4. SECOND GENERATION SPIDER ZOOM DESIGN

We extended the SPIDER concept to add a zoom capability that provides simultaneous low resolution, large field of view and steerable high resolution narrow field of view imaging modes. Fig. 3 shows our SPIDER Zoom conceptual design. The SPIDER Zoom design consists of an array of 19 high resolution PIC "cards" arranged in a radial pattern where each card contains collection optics, photonic circuits, detectors and readout electronics. Along the top of each card is a linear array of 16 "lenslet" assemblies. Each lenslet assembly is a small, compact telescope with a K-mirror for image rotation and an off-axis parabolic mirror to couple light into the waveguides on the PIC. For each high resolution card there are four low resolution cards each containing eight smaller lenslet assemblies. Each of the four cards is pointed to cover adjacent areas on the ground to increase the low resolution field of view. The first two K-mirrors of the high resolution cards are actuated to provide line of sight steering and pathlength matching for the high resolution field of view.

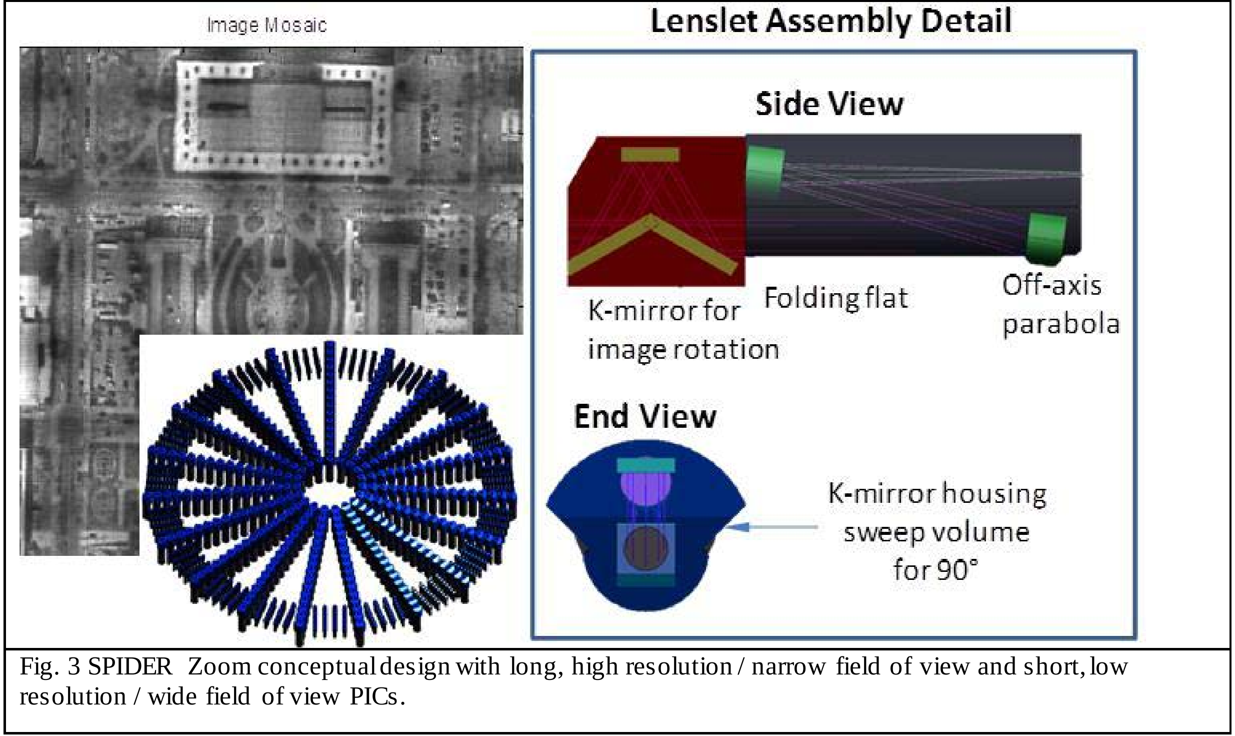

Fig. 3 SPIDER Zoom conceptual design with long, high resolution / narrow field of view and short, low resolution / wide field of view PICs.

Starting with our reference SPIDER Zoom concept, we derive a set of requirements for a demo that matures our concept by reducing the highest risks and providing validation data to our models to increase the fidelity of our performance predictions for various mission applications. By rotating the scene, or equivalently the imaging sensor, we are able to collect sufficient complex visibility data to reconstruct an entire image with only a single high resolution PIC and a single low resolution PIC. We also limit the field of view to a single field point waveguide per lens to avoid complex multi-layer fab, which is a substantial cost and risk driver. The resulting fields of view of the high and low resolution images are shown in Fig. 4.

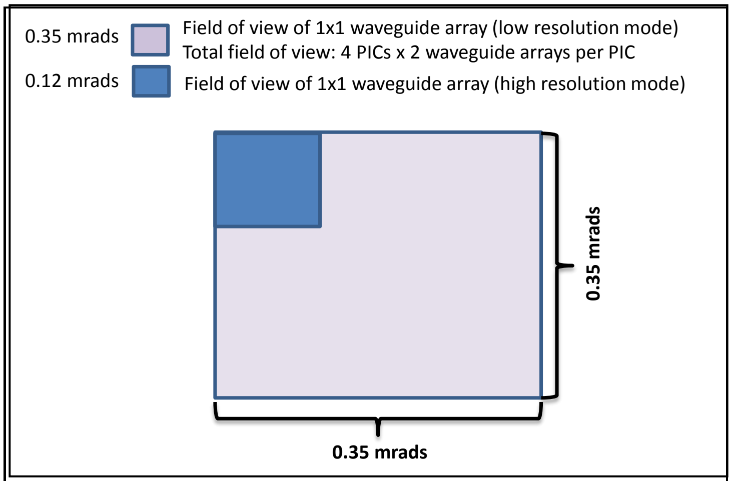

Fig. 4 SPIDER Zoom demo. The demo provides a large field of view, low resolution mode and a narrow field of view, high resolution mode with a single waveguide per lens to validate the reference design.

Starting with the initial design parameters, we derived the set of baselines, shown in Fig. 5, for use on the PIC, providing complete u-v sampling along the radial direction that roughly matches the Nyquist sampling rate. The baseline and spectral bin selections in Fig. 5 were optimized to minimize any gaps between u-v sample points. Figure 6 shows the resulting radial u-v sampling. The u-v samples are shown in units of Nyquist samples, or cycles per lenslet Airy disk diameter. There are no sample gaps between baselines and the sample spacing is roughly equal to Δu for all but the long baselines. For the longest baseline, only 18 samples span the range between 60-80 cycles/lenslet Airy disk. For a maximum spatial frequency of $80\Delta u$, the resulting image resolution would be approximately FOV/160. In other words, we would expect 160 resolution elements across an image width equal to FOV.

A high-resolution blade from the SPIDER design is composed of a linear lenslet array in front of a photonic integrated circuit (PIC). At the back focus of each lenslet is a waveguide input that collects light from a field point in the scene. The light from a pair of lenslets (e.g., +1 & −1, …, +11 & −11) that form a baseline is combined interferometrically with appropriate phase shifts to create complex (amplitude and phase) fringe signals. A series of arrayed-waveguide gratings (AWGs) spectrally demultiplex the interferometer outputs into 18 spectral bins (passbands) and a detector array captures the spectrally demultiplexed fringe signals for processing.

To summarize, the PIC performs the following optical processing 1) collect light into wave-guides, 2) apply phase shifts to the light, 3) coherently combine baseline pairs (lenslets with different separation), 4) demultiplex the light into spectral bins, and 5) photodetection of the complex fringe pattern. This processing sequence is different from the previous SPIDER PIC designed for the DARPA SeeMe project which placed the spectral demultiplexers before the interferometers (2×2 MMIs). By moving the 2×2 MMIs and the phase shifters before the spectral demultiplexers, only a number of heaters equal to the number of baselines is required (in contrast to baselines times spectral bins, previously).

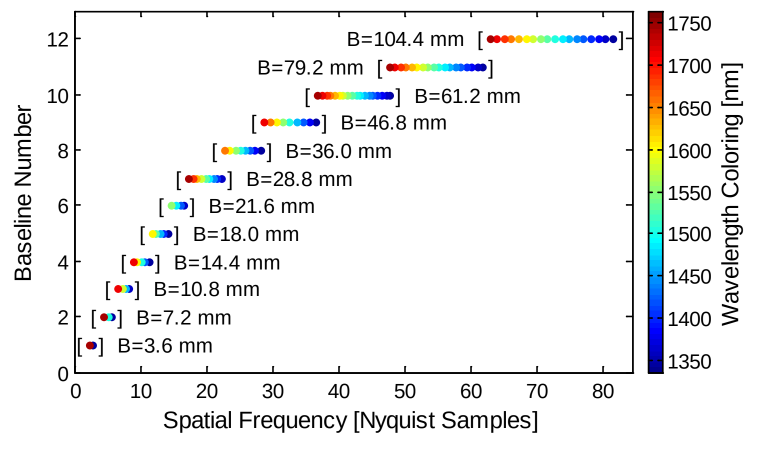

Fig. 5 SPIDER Zoom baseline length and spectral bins.

Performing similar optical processing operations with integrated photonic devices has already been well demonstrated in various material platforms (e.g., indium phos-phide (InP), silicon (Si), silica (SiO2), and silicon nitride (SiO3N4)) [1-5]. Of particular interest for the proposed project, is silicon nitride with a silica cladding. This material platform provides transparency in the visible and near-infrared spectral bands as recently demonstrated by the UC Davis multi-layer fabrication capability.

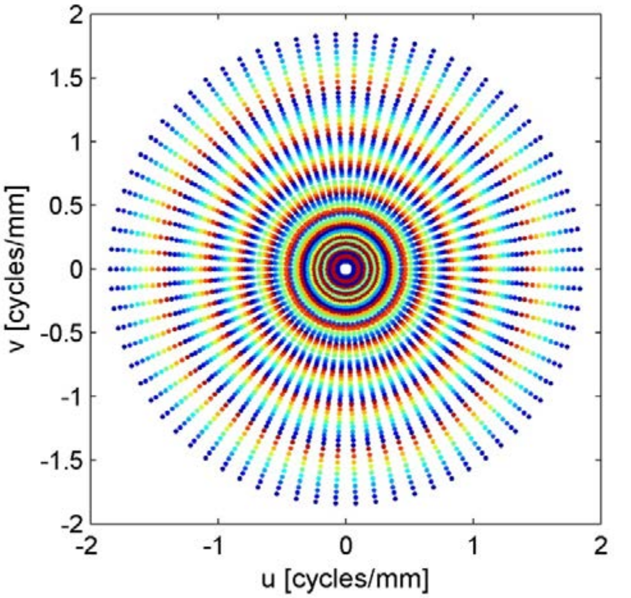

Fig. 6 SPIDER Zoom sampling in the u-v plane; u-v sampling obtained from various baselines and spectral bins provides sufficient coverage to enable a high quality image reconstruction

5. SUMMARY AND CONCLUSIONS

Prior LM IRAD and DARPA/NASA CRAD-funded SPIDER risk reduction experiments, design trades, and simulations have matured the SPIDER imager concept to a TRL 3 level. Current funding under the DARPA SPIDER Zoom program is maturing the underlying PIC technology for SPIDER to the TRL 4 level. This is done by developing and fabricating a second generation PIC that is fully traceable to the multiple layers and low-power phase modulators required for higher dimension waveguide arrays that are needed for higher field of view sensors. Our project also extends the SPIDER concept to add a zoom capability that provides simultaneous low resolution, large field of view and steerable high resolution narrow field of view imaging modes. A proof of concept demo is being designed to validate this capability. Data collected by this project will be used to benchmark and increase the fidelity of our SPIDER image simulations and enhance our ability to predict the performance of existing and future SPIDER sensor design variations. These designs and their associated performance characteristics can then be evaluated as candidates for future mission opportunities to identify specific transition paths.

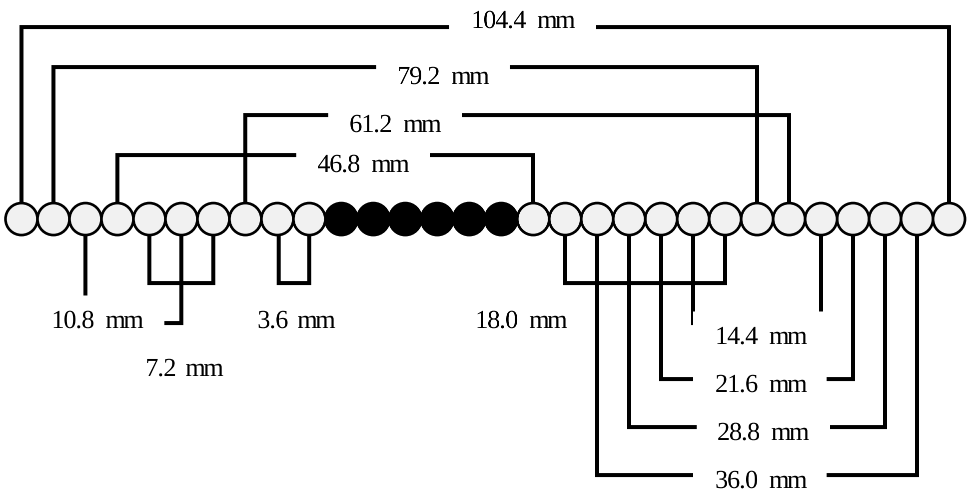

Fig. 7 SPIDER Zoom high resolution PIC baseline layout. The low resolution PIC has an identical baseline layout reduced in scale by a factor of 5.

6. REFERENCES

7. ACKNOWLEDGEMENTS

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions, and/or findings contained in this material are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.