

PROGRESS REPORT

Low-Mass Planar Photonic Imaging Sensor

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Technical Point of Contact

Professor S. J. Ben Yoo
University of California
Dept. of Electrical and Computer Engineering
Kemper Hall, Rm 3179
Davis, California 95616
Tel: 530-752-7063
Fax: 530-752-8428
E-mail: sbyoo@ucdavis.edu

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2. Summary

Continuing on the successful progress of NIAC Phase I, this report summarizes the technical progress achieved under NIAC Phase II during the performance period September 19, 2014 – June 18, 2017.

During this period, the research team has made the following accomplishments:

- designed and layout a silica photonic integrated circuit (PIC) as a two baseline interferometric imager,
- constructed an experiment to utilize the two baselines for complex visibility measurement on a point source and a variable width slit,
- analyzed and studied the testbed results. (*in collaboration with Lockheed Martin*),
- designed and layout Si_3N_4 PICs for the low-resolution and high-resolution SPIDER telescope ,
- fabricated the multi-layer Si_3N_4 PIC for low and high resolution SPIDER telescope,
- characterize the optical throughput and heater response for Si_3N_4 PIC for low and high resolution SPIDER telescopes,
- carried out imaging experiments using the Si_3N_4 PIC low-resolution version (*in collaboration with Lockheed Martin*),
- investigated signal-to-noise (SNR) ratio of SPIDER imager compared to the conventional panchromatic imager (*in collaboration with Lockheed Martin*),
- fulfilled the SNR simulation upon SPIDER imager (*in collaboration with Lockheed Martin*).

3. Technical Progress

3.1. Silica PIC device

The interferometry techniques use superimposed electromagnetic waves to extract information of the wave source. In astronomy, an interferometer uses far-field spatial coherence measurements to extract intensity information from a source to form an image. Examples include the Very Large Telescope Interferometer, the Navy Precision Optical Interferometer, and the Very Long Baseline Interferometer. These systems use meter-class telescopes to collect light and have interferometer baselines on the order of 10 m ~100 m. Often, measurements are made only using a few telescopes at a time over long imaging campaigns. Complex beam combination systems with long adjustable delay lines are needed for optical path length matching when viewing objects in different parts of the sky.

Recently, we proposed the concept of a Segmented Planar Imaging Detector for Electro-optical Reconnaissance (SPIDER). SPIDER is a small-scale interferometric imager that uses a lenslet array to simultaneously form many interferometer baselines and photonic integrated circuits (PICs) to miniaturize the beam combination hardware. Simultaneous measurements on several baselines in two dimensions will eventually enable snapshot imaging. By designing SPIDER as a common mount system, with a fixed boresight for each lenslet, the beam combination hardware can be greatly simplified by eliminating the need for long adjustable delay lines. The whole system can be rigidly pointed to look in different directions.

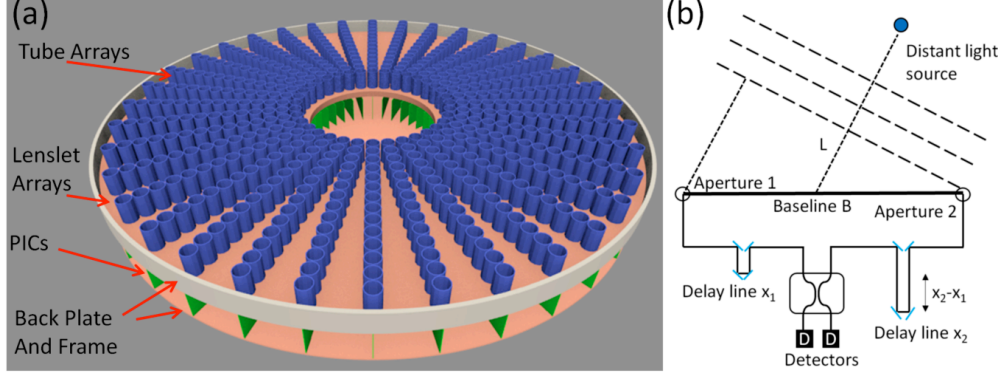


Fig. 1. (a) The schematic diagram of the SPIDER telescope. (b) A two-aperture interferometry system.

Our long-term goal is to develop SPIDER as an alternative to conventional optical telescopes. Consisting of large optics, supporting structures, and precise thermal controls, conventional optical telescopes can be bulky, heavy, and power consuming. For instance, the Hubble telescope has a total mass of 27,000 pounds, its primary mirror is 2.4 m across, and the telescope is 13.3 m long. The interferometric imaging telescope of the same diameter (baseline) can achieve the same resolution but avoids the need for large lenses or reflectors contained in a large tube structure that must maintain a rigid structure across the ambient temperature range. As we will discuss below, the interferometric imaging telescopes based on PICs have the potential to reduce the size, weight and power (SWaP) compared to a conventional telescope with similar effective aperture and spatial resolution. The SPIDER concept, illustrated in Fig. 1(a), describes a Fourier-domain interferometric imaging telescope that utilizes photonic integrated circuits (PICs) to directly detect white-light interference patterns. Light from a scene is coupled through multiple pairs of separated lenslets into waveguides on a PIC chip and combined to form the interference pattern. By measuring the interference pattern from these baselines, the intensity distribution of the scene can be reconstructed.

In this paper, we demonstrate a one-dimensional interferometric imaging PICs and use it in a proof-of-concept interferometry experiment. Such PICs are the building blocks of a complete SPIDER telescope, in which they provide spectral filters, optical phase modulators, and light combiners on the same chip. Realizing these PICs is a significant step towards realizing a complete SPIDER telescope.

3.1.1. The SPIDER concept

The basic concept of the SPIDER device is optical interferometry. Figure 1(b) shows a simple two element system with a distance source, two apertures, two tunable delay lines, a beam combiner, and two detectors. As the delay line length on one of the two arms changes, the combined beam intensity I_{tot} also changes.

$$I_{tot} = I_1 + I_2 + 2\sqrt{I_1 I_2} |\gamma_{12}| \cos \left\{ \frac{2\pi}{\lambda} [\vec{L} \cdot \vec{B} + x_1 - x_2 + \arg(\gamma_{12})] \right\} \quad (1)$$

where L is a unit vector that represents the line of sight of the interferometer (L points from the interferometer towards the object), B is the interferometer vector baseline, x_1 and x_2 are the optical path lengths through the interferometer for the light collected by apertures 1 and 2, respectively. The dot product $L \cdot B$ term in the cosine argument represents the free space optical path difference associated with the viewing geometry, while the $x_1 - x_2$ term represents the

compensating delay associated with the delay lines. The I_1 and I_2 terms represent the intensity throughput for each arm of the interferometer. The γ_{12} term is the complex degree of coherence, which represents the coherence between the light collected each aperture. In Goodman's notation, γ_{12} would be replaced with the mutual intensity function. Note that Eq. (1) only represents the intensity at one output port of the interferometer. Fringes measured at the other output port will be π out of phase with respect to this expression.

$$abs(V) = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} |\gamma_{12}| \quad (2)$$

The term $2\sqrt{I_1 I_2} / (I_1 + I_2)$ is the visibility associated with unequal beam intensities in the interferometer, which can be characterized through calibration measurements. γ_{12} is related to the source intensity distribution through a Fourier transform relationship by the van Cittert-Zernike Theorem. The phase of the fringes is related to the phase of γ_{12} through Eq. (1). Images are formed by measuring the complex fringe visibility from many different baselines, thereby building up an estimate of the 2D spatial Fourier transform of the source distribution. Inverse Fourier transform of the complex visibility then yields the source brightness distribution. Figure 2(a) shows a layer-by-layer description of a conceptual SPIDER telescope design. The top layer is the tube arrays that block stray light from the detectors. The second layer is a lenslet array plate, focusing the collimated light on the input waveguides of PICs. Each PIC is a one-dimensional interferometer by itself and is held in position by the inner and outer align cylinder. The PICs are arranged in a radial pattern to thoroughly sample the target's two-dimensional spatial frequencies. The back plate contains readout and digital signal processing (DSP) electronics. The conceptual SPIDER imager uses multiple baselines to sample the target visibility function in the spatial frequency domain, then digitally reconstructs the object image.

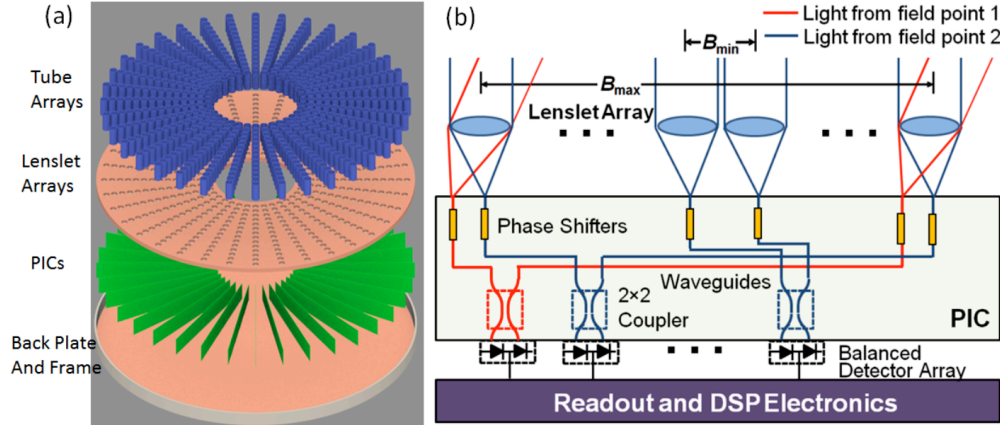


Fig. 2. (a) Layer-by-layer break down of the SPIDER telescope. (b) Working principle of the PIC.

The PICs translate target intensity distribution into Fourier domain information. Figure 2(b) shows the working principle for one of the PICs in the SPIDER concept. $B_{\min}$ and $B_{\max}$ are the minimum and maximum interferometer vector baselines of the PIC. Each PIC aligns to a focusing lenslet array with matched lens spacing. This lenslet array contains multiple lenslet pairs, and each pair gathers light from a given baseline value. Behind each lenslet, there are multiple receiving waveguides with small spacing. Each waveguide collects light from a different field of view (FOV). The PIC combines the paired beam in 2x2 couplers, then measures the output using balanced photodetector arrays. By scanning the phase delay on one of the arms

in the combiner, the balanced detectors receive fringe information, from which we calculated the phase and amplitude of the object visibility function. Then we reconstructed the target intensity distribution using visibility functions in the spatial frequency Fourier plane (the uv -plane).

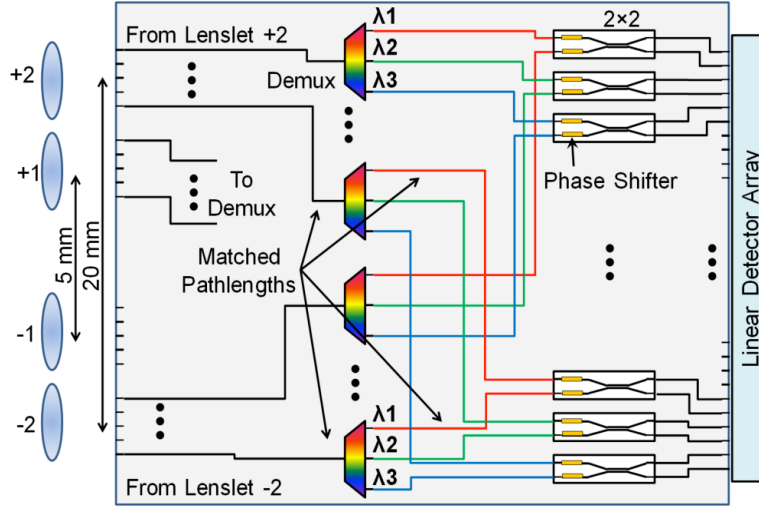


Fig. 3. A schematic functional diagram of the PIC [7].

As a first initial milestone toward realizing the full SPIDER telescope, we demonstrated a PIC that has the same functionality as the proposed PICs in Fig. 3. We tested the performance of spectral filters, optical phase modulators and light combiners on this PIC. Compared to the proposed PICs in Fig. 2(a), the demonstrated device has a fewer number of baselines, a fewer spectral channels, and an off-chip detector array.

3.1.2. PIC design and layout

Figure 3 shows the functional diagram schematic of the PIC. The PIC is designed for a silica PIC platform with 1.5% refractive index difference of the core and cladding. The single mode waveguides are $4.8 \mu\text{m}$ wide and $5.2 \mu\text{m}$ thick. The components on the PIC include (from left to right) spectral demultiplexers, photonic delay lines, optical phase shifters, and beam combiners. The PIC has two physical baselines (5 mm and 20 mm separation), three spectral channels (centered at 1540 nm, 1560 nm, and 1580 nm) and five waveguides after each lenslet. The maximum interferometer baseline determines the spatial resolution of the imager. The demultiplexers separate the beam into three spectral channels, followed by a 2×2 interferometer array which combines light from corresponding input waveguides. The detectors capture light from the outputs, and data processing computer calculate fringe information.

The working principle of PIC in Fig. 3 is similar to that of Fig. 2(b). There are four input waveguide groups (one group for each lenslet) with five waveguides ($20 \mu\text{m}$ spacing) in each group. Each input waveguide connects to a demultiplexer, which is a thermally tuned two-stage asymmetrical Mach-Zehnder interferometer (MZI). The demultiplexer has three channels centered at 1560 nm with 20 nm channel spacing. Fringe formation from incoherent sources can be measured only if the waveguides from the input to the 2×2 interferometer are path-length matched to less than the coherence length, which is $l_{coh} = \lambda^2 / \Delta\lambda \approx (1550 \text{ nm})^2 / 20 \text{ nm} \approx 120 \mu\text{m}$. Widening the demultiplexer spectral channels or removing the demultiplexer will increase the optical power received at the output detectors, but reduce the coherence length l_{coh} and place a tight constraint on waveguide routing and fabrication. Thus we designed two sections of delay

lines in opposite directions to achieve equal optical path length between interference waveguides. A thermo-optic phase shifter steps the phase of one interferometer input to generate the raw complex visibility fringe. 100 μm wide, 20 μm deep trenches are placed next to the phase shifters to improve phase shifter efficiency. Additional trenches help to block stray light from reaching the detector. Finally, the output waveguides (200 μm spacing) are tapered in the horizontal direction to expand the output mode to 70 μm wide ($1/e^2$ width of intensity). This positive adiabatic taper reduces the optical mode expansion in the gap between the PIC facet and the detector array.

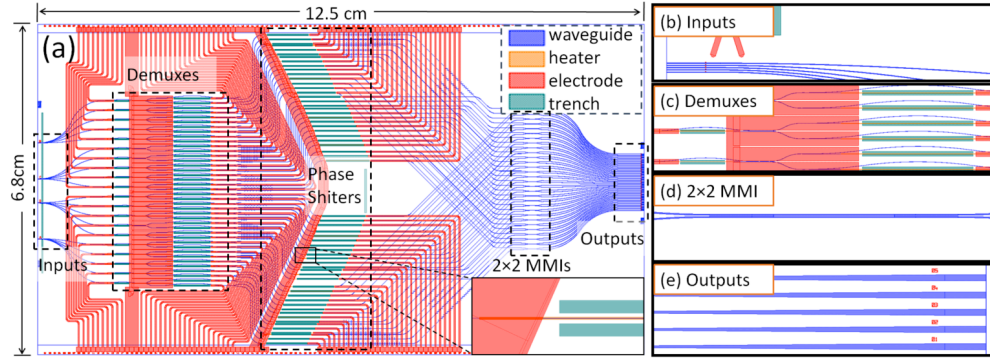


Fig. 4. (a) The mask layout of the fabricated PIC. (b)-(e) Zoom-in layouts showing a group of five inputs, the demultiplexers, a 2 $\times$ 2 MMI and a group of outputs.

Figure 4 shows the PIC layout for fabrication. Fabricating this device uses four mask layers: waveguide, heater, electrode, and trench layers. A commercial foundry fabricated the device on a low-loss silica waveguide platform, on which the core to cladding index contrast is 1.5%. Silica PIC platform is a well-developed integrated optics platform, offering low-loss passive components and efficient thermos-optic phase shifters. It allows us to fabricate future devices with a baseline larger than 20 mm. The silica waveguides exhibit weak optical mode confinement in the core region, and less polarization dependence than similar devices on silicon or InP platforms. We also included various test structures in this fabrication run, which allow us to characterize individual PIC components.

3.1.3. PIC Characterization

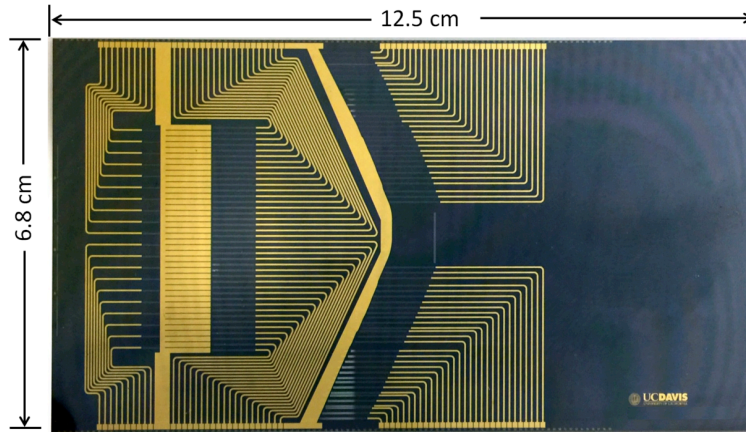


Fig. 5. Fabricated silica SPIDER PIC.

Figure 5 shows the fabricated silica SPIDER PIC. We characterized the device performance using an optical vector network analyzer (OVNA). We inspected the waveguide propagation loss, crossing loss, mode profile, and spectral demultiplexer. We launched 1550 nm TE-polarized laser light into the PIC using a cleaved single mode optical fiber, then used another single mode fiber to capture the output light into a power detector. The measured PIC total insertion loss is about 5 dB, including both waveguide propagation loss and crossing loss. The measured silica waveguide propagation loss is ~ 0.07 dB/cm. The coupling loss is 0.8 dB between fiber and the single mode waveguide. Figure 6(a) shows the optical loss caused by waveguide crossing at different crossing angles, both from simulation and from actual measurement on test structures. Artificial crossings were designed so the interference arms have equal optical loss from crossing. Each interference arm goes through fifteen 45° crossings and thirty 90° crossings, which adds up to ~ 3.8 dB loss from waveguide crossings. Figure 6(b) shows the MZI performance measured from test structures. The transmission peaks are 1550 nm, 1567 nm, and 1584 nm. The channel spacings are 17 nm, slightly less than the simulated 20 nm. The neighboring channel crosstalk is 10 ~ 15 dB.

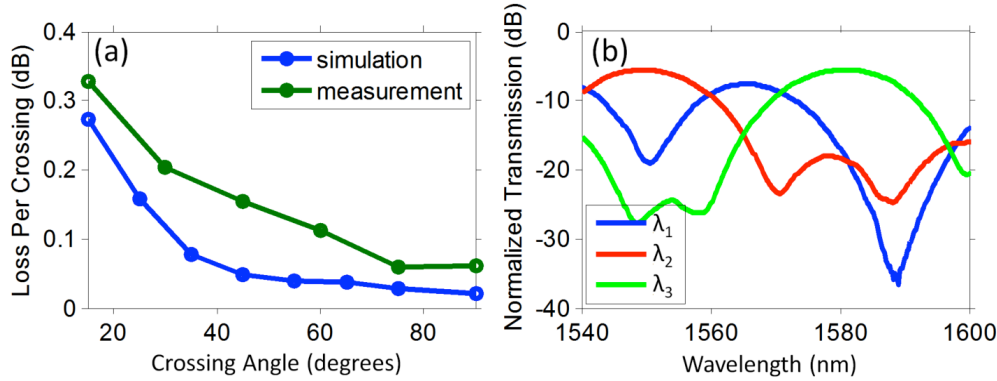


Fig. 6. (a) Measured and simulated waveguide crossing loss. (b) Measured 1×3 demux MZI performance.

Figure 7(a) shows the measured optical output fringe at different heater power with input wavelength $\lambda = 1562$ nm. The heater power required for a π phase change is about 1.1 W. The required electrical power for thermal tuning is rather high on this PIC. It currently does not limit the PIC performance, since the thermal phase shifters are used one at a time. For future larger scale PICs, the thermal tuning efficiency can be improved through using thinner waveguide upper cladding. For more detailed studies, a series of spectra were recorded for different heater powers. Figure 7(b) shows the measured phase shifter characterization with heater power 0 to 1.6 W and wavelength 1550 nm to 1585 nm.

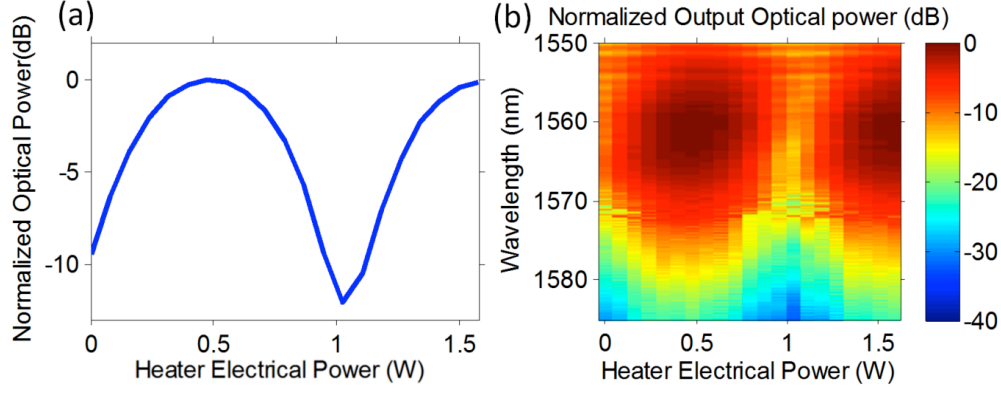


Fig. 7. (a) Measured Heater phase shifter performance for $\lambda = 1562$ nm. (b) Measured heater phase shifter performance for $\lambda = 1550$ nm $\sim$ 1585 nm.

Figure 8 shows the input and the output waveguide mode. To reduce coupling loss, the input waveguide mode match with the focused beam profile from the lenslet. The measured mode size is $6.0 \mu\text{m} \times 7.3 \mu\text{m}$. The output waveguide mode, after spreading over a short propagation distance, fits in the pixel of our linear detector array. The detector array has 256 photodetectors pixels, and each pixel is $50 \mu\text{m} \times 500 \mu\text{m}$ in size. The measured output waveguide mode size is $61 \mu\text{m} \times 7.0 \mu\text{m}$.

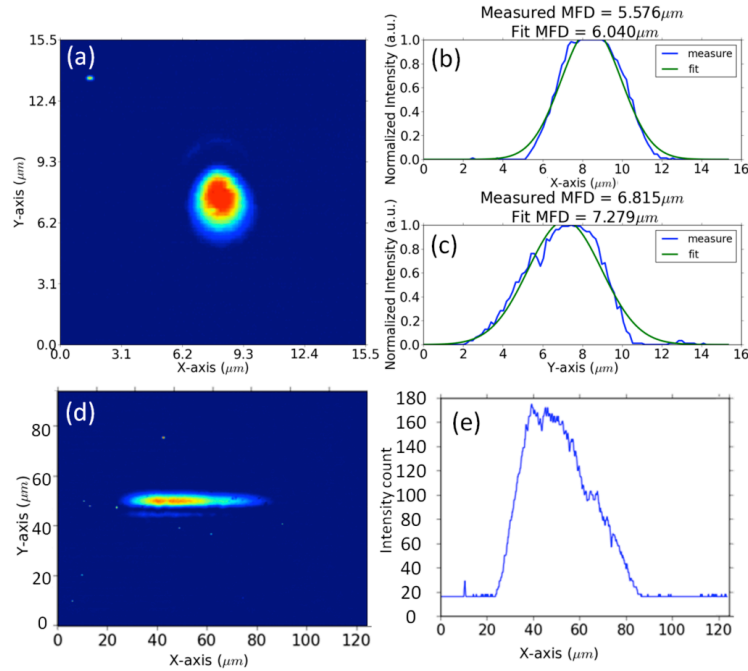


Fig. 8. Measured waveguide optical mode profiles. (a) Input waveguide 2D mode profile. (b)(c) Input waveguide mode field diameter (MFD) in x-axis and y-axis. (d) Output waveguide 2D mode profile. (e) Output waveguide mode profile in x-axis.

3.1.4. Testbed Experimental Arrangement

To prove that the PIC is a feasible option for interferometric imaging, we constructed a testbed capable of demonstrating the long-baseline interferometry with both finite and extended scenes. The first step is to generate the broadband extended scene, as shown in Fig. 9(a). We used a

broadband incoherent lamp to illuminate the scene, which is locked on a long travel 1-D stage. The light beam from the scene passes through a telescope system before being captured by the lenslets. The scene is placed at the focus of the telescope, so the PIC is located in the far field of the scene.

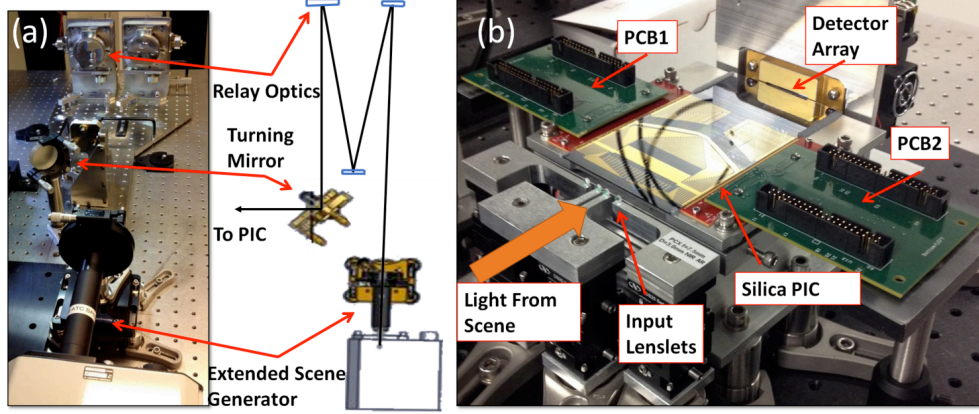


Fig. 9. (a) Photo of the extended scene generator and its schematic diagram showing the optical beam path. (b) Photo of the packaged PIC on its holding. The PIC is shown in the center with the lenslets at the front, the detector array at the back and the two PCBs on the side.

Figure 9(b) shows the packaged PIC without its housing and baffles that protect it from stray light. Aligning the scene generator, the telescope, and the lenslet array requires both stability and fine control in each component. The four lenslets ($D = 3$ mm, $f = 7.5$ mm) are each located on a separate 3D stage and independently aligned for optimum coupling to a common FOV. The PIC is mounted on an Aluminum heat sink, whose temperature is fixed at 27° C. The electrodes on the PIC are wire bonded to two PCBs, which allows simultaneous control of phase shifters and MZI demux wavelength tuning. The two PCBs connect the PIC electrode pads with the computer-controlled electrical power sources. A black plastic box (not shown in the photograph) covers the lenslets, the PIC, and the detectors to block stray light. The complementary outputs from all 2×2 couplers are butt-coupled to an InGaAs linear detector array. The gap between PIC output and the detector is 2.5 mm wide. Detector arrays are mounted in a housing with a window for protection and a heat sink for cooling to -5° C. For optimum mode match, we designed the waveguide pitch to be 200 μ m and the output mode width in x-axis to ~ 70 μ m. With a ~ 2.5 mm gap between the PIC and array, each output waveguide illuminates three pixels on the detector array.

The testbed requires multiple steps of alignment. We first aligned the three concave mirrors as a telescope on a separate optical table. After back propagating He-Ne laser light through the PIC and towards the object, we aligned all four lenslets one-by-one by focusing He-Ne light to the same point in the object plane. Finally, we fixed the detector array at PIC output.

3.1.5. Testbed Results

Firstly we studied the fringe data of a point source. Figure 10(a) shows the measured raw fringe data. As the thermal tuner steps the phase of the interference arm, we measured the photometric counts from an output port. I_1 and I_2 are measured with light coming through individual lenslets. There is no interference of light for these measurements, so the recorded signal levels are stable, regardless of the phase step. I_{tot} is measured with light from both lenslets of a baseline. We

normalized I_{tot} against I_1 and I_2 using Eq. (3). Comparing Eq. (1) and (3), we can see that the amplitude and phase of the normalized fringe are directly related to the coherence term in Eq. (1), which is what we wish to measure. Figure 10(b) shows the normalized data and a sinusoidal fit.

$$I_{norm} = \frac{I_{tot} - I_1 - I_2}{2\sqrt{I_1 I_2}} \quad (3)$$

We tested the system with both short (5 mm) and long (20 mm) baselines. The measured point source visibility is 0.94 for the short baseline and 0.90 for the long baseline, representing the system instrumental visibility. Ideally, the measured visibilities would equal unity. The instrumental visibility can be reduced by residual optical path difference (OPD), dispersion, scattering, and polarization effects. We consider values of 0.94 and 0.90 to be quite large and an indication of the high quality of the PIC.

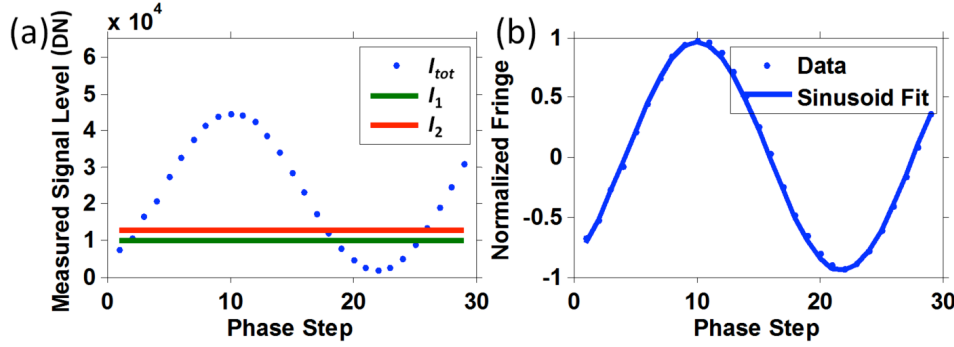


Fig. 10. Fringe measurement result (a) before normalization in data numbers (DN) and (b) after normalization.

The field of view of the device limits how much light the PIC receives when the point source shifts in the object plane. Figure 11(a) shows light intensity change for all four lenslets when the point source position changes. Measured device FOV is $1500 \mu\text{m}$, limited by the focal length of the scene projector telescope, the lenslet numerical aperture, and the waveguide numerical aperture. The plot indicates that the coupling efficiency and the throughput for light collected by different lenslets varies by up to a factor of 3. The curves also indicate that the lenslets are fairly well aligned (at least along the direction of measurement) to a common point in the object plane. This is important because the lenslets need to collect from a common FOV in order to see fringes at the PIC output waveguides. Figure 11(b) shows that the measured visibility drifts for both baselines are less than 5% within this point source position range. The theoretical point source visibility is 1, independent of its position.

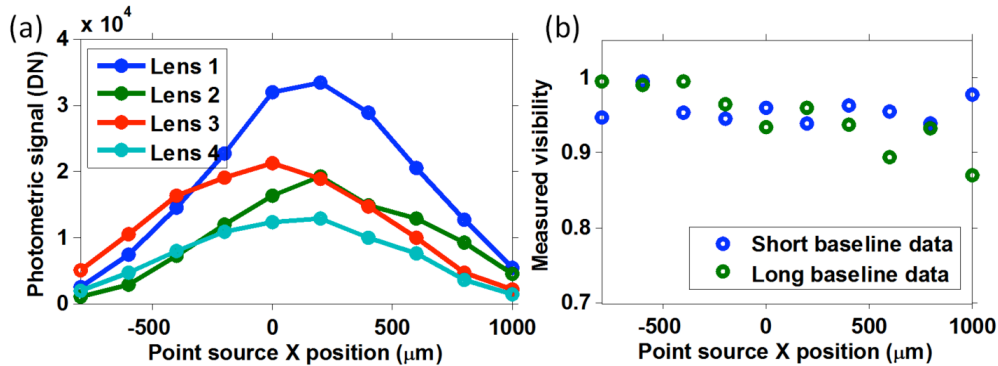


Fig. 11. (a) Received output power and (b) visibility as we moved the point source position.

We measured fringe data with the point source in different positions. As shown in Eq. (1), the observed fringe phase is expected to vary with the point source position x as

$$\Delta\phi = \frac{2\pi}{\lambda} \vec{L} \cdot \vec{B} \approx \frac{2\pi}{\lambda} \frac{\Delta x}{F} B \quad (4)$$

Eq. (4) assumes a small angle approximation. The point source position shift translates to phase shift of the sinusoid fringe pattern. Figure 12 shows the unwrapped fringe phase at different point source positions. As predicted, it shows a linear phase shift. The calculated point source to PIC distance is 1535 mm, matching the scene generator design.

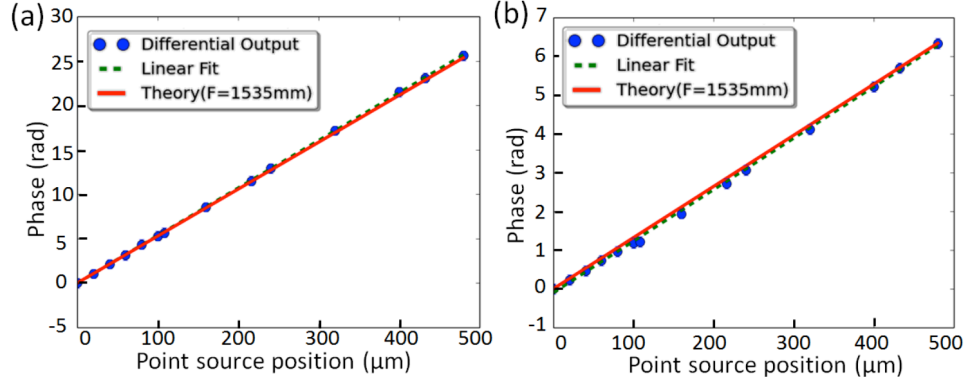


Fig. 12. Relative phase of complex visibility for different point source positions (a) Baseline width $B = 20$ mm (b) Baseline width $B = 5$ mm

Then we studied the fringe data from a variable width slit. Figure 13(a) shows the amplitude of the target visibility as a function of slit width for two baselines. Because the scene is a rectangular aperture, the theoretical single baseline visibility traces a sinc curve as a function of aperture width.

$$V = \text{sinc}\left(\frac{wB}{\lambda F}\right) \quad (5)$$

Here V is the visibility, w is the slit width, B is the baseline width, and F is the distance between slit and aperture. The measured data provide good agreement with Eq. (5). The visibility peaks of the short baseline are $\sim 20\%$ lower than ideal, and that of the long baseline is $\sim 60\%$ lower than ideal. For the short baseline, the first three null point locations (slit width values) are within 6–8% of the theoretically predicted values. For the long baseline, the first three null points are within 3–4% of the theoretically predicted values.

Figure 13(b) shows the phase of the target visibility as a function of slit width for both baselines. In theory, the phase traces a setup curve as a function of the aperture width. The measured data shows good agreement with theoretical predictions. The following section discusses the smoothness of the measured phase data.

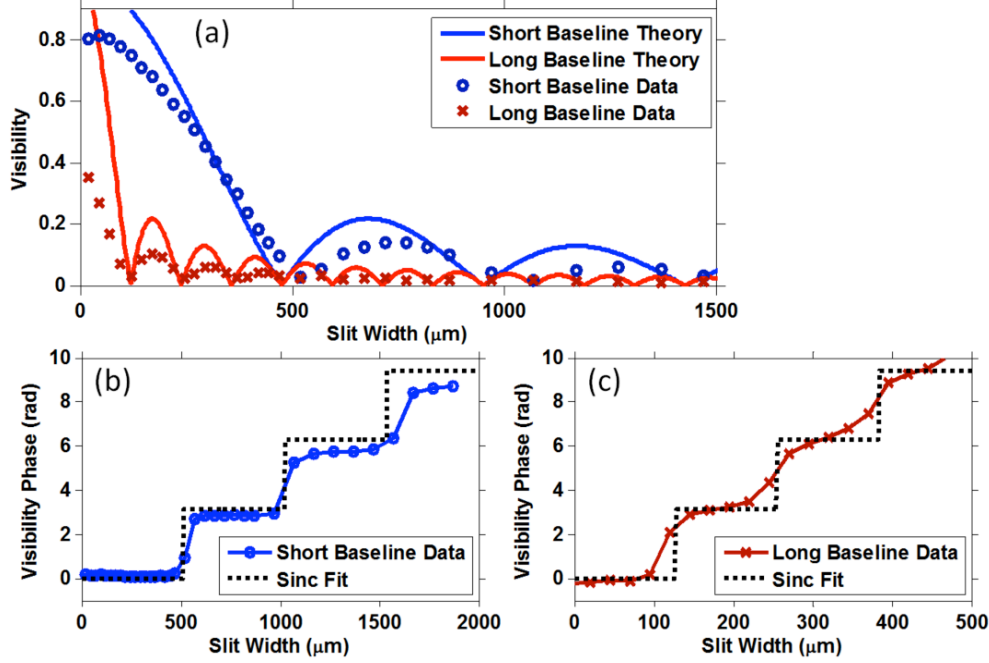


Fig. 13. (a) Visibility magnitude of a variable width slit for both baselines [7]. (b) The visibility phase of a variable width slit for baseline width $B = 5$ mm. (c) The visibility phase of a variable width slit for baseline width $B = 20$ mm.

3.1.6. Study of the results:

We measured the visibility of a point source and a variable width slit with a two baseline interference PIC. As shown in Fig. 13, we observed the visibility intensity plots have null points not reaching zero, and the visibility phase plots have traced a smooth curve instead of a step trace. The slit center having an offset from the field of view center can cause the non-ideal effect in Fig. 13. Figure 14 contains simulation results that provide a possible explanation for some of the effects seen in the experimental data. Figure 14(a) illustrates how the scene as viewed by the system is the product of the object intensity distribution and an apodization function that describes the system FOV. Figure 14(b) and Fig. 14(c) show how the visibility measurements are affected by an offset of the common field of view of the PIC. As the offset increases, the nulls in the visibility magnitude washout and become local minima. Also, the sharp π phase transitions in the visibility phase function turn into smooth transitions. The experimental results shown in Fig. 13 exhibit both of these effects. Comparison of the simulation and experimental results suggests that there might have been as much as a $500 \mu\text{m}$ offset between the system FOV and the center of the variable slit.

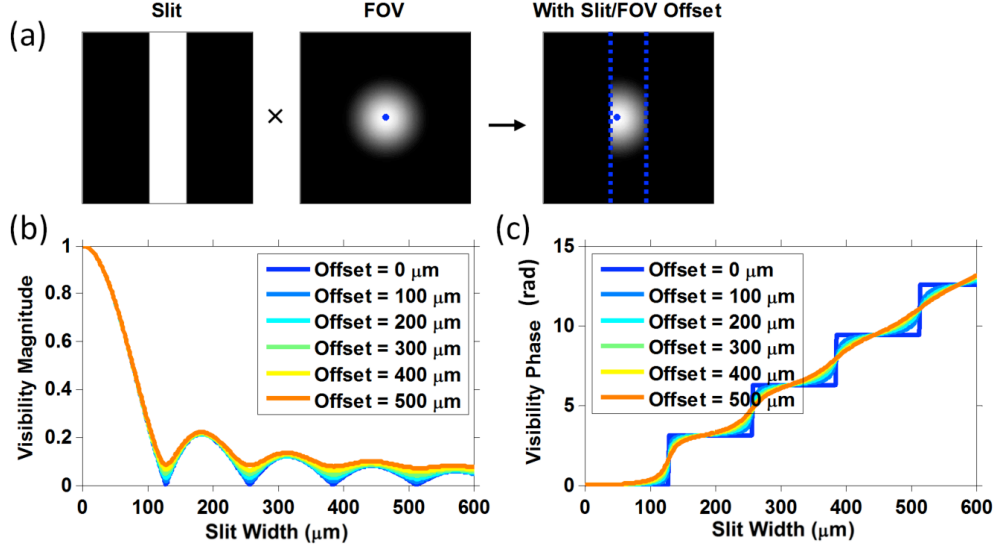


Fig. 14. (a) Schematic of misalignment between slit and FOV. (b) Simulated visibility intensity for different slit to FOV misalignment. (c) Simulated visibility phase for different slit to FOV misalignment.

These simulations only examine the effect of an offset between a common system FOV and the scene. If the individual lenslets have slightly different FOVs, then they will collect light from different parts of the scene, which will reduce the overall magnitude of the observed fringe visibility. This can explain the low object visibilities seen in the experimental data, considering that the slit visibilities for the 5 mm and 20 mm baselines are about 20% and 60% lower than expected. The data in Fig. 11(a) shows that lenslet FOVs are aligned within approximately 200 μm along the x direction. We studied the received photometric signal intensity as a function of slit width at different slit to FOV offset. We estimated the offset is less than 500 μm for all four lenslets. This measurement helped us improve the alignment accuracy of individual lenslets.

3.1.7. Future Devices with A Large Number of Baselines

In this work, we designed interference PIC with two baselines and demonstrated visibility measurements with a point source and a variable width slit. The PIC measures two data points of a far field scene's Fourier domain information. To sample more data points in the u - v plane and then to reconstruct a complete image, we need to increase the number of baselines and demultiplexer channels. When scaling the device to more lenslet pairs and more wavelengths, the number of waveguide crossings scales as well. The crossing loss will be a limiting loss factor in future device design. PIC technology with multiple waveguide layers can help significantly eliminate the crossing loss.

In summary, we proposed the concept of a SPIDER imager that has the potential to reduce SWaP compared to conventional telescopes. We demonstrated a PIC that shows much of the functionality needed to implement the SPIDER imager. The imaging testbed results show interferometric imaging for both point sources and extended scenes. In-depth study of the measured data indicates that we understand device performance. Future work will add additional baselines to the PIC designs to image more complex scenes.

3.2. Si₃N₄ PIC Device

3.2.1. SPIDER concept

Figure 3.2.1 expands our proposed system into different components in a top-down view. The system consists of various 1D interferometers arrays arranged in the radial pattern. Many interferometer tube assemblies at the top contain all necessary lenslets to couple light into the PICs waveguides. A lenslet array plate is designed accordingly to firmly hold the interferometer tube assemblies. The outer and inner align cylinder is inserted to maintain the alignment and collimation between lenslets and PICs. Then various PICs are held in between aligning cylinders to fulfill the spatial resolution. All above components sit on a stiff back plate which contains readout and Digital Signal Processing (DSP) electronics. The overall system form factor is comparable to a flat screen TV or solar panel. The spatial resolution of the whole system is determined by the maximum interferometer baseline distance in an individual PIC and is comparable to the conventional aperture having the diameter approximately equal to this maximum baseline distance.

Within a single PIC, the image field-of-view (FOV) is determined by the light coupling efficiency into the PIC as a function of the field angle. This coupling efficiency is calculated through the overlap integral upon the designed waveguide mode and the lenslet Airy-disk spot pattern at different field angles. The FOV of a single chip is close to the angular diameter of the Airy function, *i.e.*, $FOV \sim 2.44 \lambda / d$, where λ is the imaging wavelength and d is the relevant lenslet diameter when the lenslet f-number is chosen to maximize the coupling efficiency between lenslet Airy-disk spot and the waveguide mode.

The resolution of a SPIDER imager is determined by the imaging wavelength λ and the maximum baseline distance B_{max} . The complex degree of coherence $j(\mathbf{B})$ is a function of the 2D vector baseline separation $\mathbf{B}$ between each pair of lenslets, which maps to a corresponding angular spatial frequency as $u = B_{max} / \lambda$. The cutoff frequency is then determined by $u_{cutoff} = B_{max} / \lambda_{min}$, where λ_{min} is the shortest wavelength of light used in the system. The resolution is comparable to the conventional imaging system when $B_{max} = D$, where D is the aperture size of the conventional imaging system.

The imaging performance of the whole system is determined by the Fourier sampling density relative to the Nyquist rate. The Nyquist rate in SPIDER system is related to the system FOV by $\Delta u = 1/FOV$. Images with high quality could be generated from sparse data using compressive sensing concepts when the dense Fourier sampling rate is close to the Nyquist rate. The SPIDER design will utilize dense radial sampling and coarse azimuthal sampling to retrieve the imaging data. Sampling along the radial direction is determined by the selection of lenslet-pairs which form the interferometric baselines. We also drive the PIC with large optical bandwidth to enhance the sampling for individual baseline. An iterative process is used to determine the baselines and spectral channels that provide nearly continuous sampling at the Nyquist rate along the radial direction. The azimuthal sampling rate depends on the actual number of radial-spoke PICs used in the SPIDER system. The number (K) of required PICs at the cutoff frequency is given by $K = \pi u_{cutoff} / \Delta u$. Achieving this exact number of PICs within the SPIDER system could provide Nyquist sampling at the cutoff frequency but oversample at lower frequencies. In practice, we will use fewer PICs number compared to K and rely on compressive sensing techniques for imaging reconstruction. We will also investigate the imaging artifacts induced by this fewer PICs number and develop corresponding DSP methods to mitigate them.

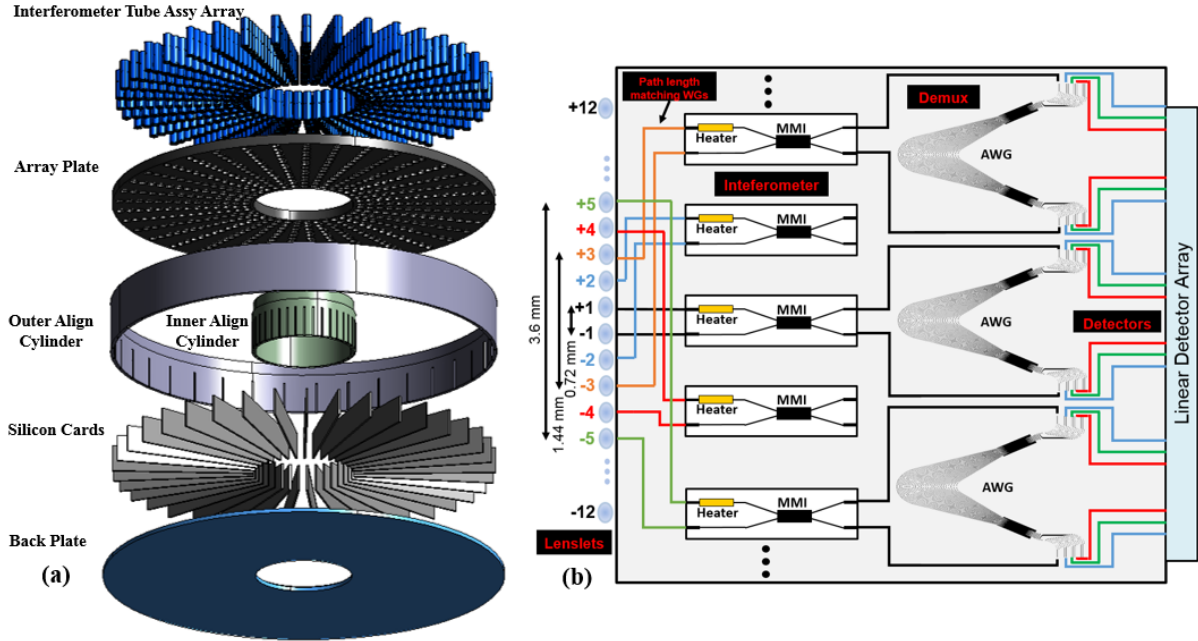


Figure 3.2.1 (a) Explode view of SPIDER system payload design (b) Si₃N₄ version SPIDER PIC design sketch

Figure 3.2.1(b) illustrates the components within a single PIC for the SPIDER system including path-length-matched waveguides, interferometers (MMIs), arrayed waveguide gratings (AWGs) based demux and detector arrays. The light is coupled from free space to waveguides on chip through various lenslets marked from -12 to +12 on the left-hand side of Figure II. A.2.3. In this PIC design, we include total 12 baselines marked by the 12 different numbers where the minimum baseline distance is 0.72mm. The rest 11 baselines' distances are integer times of the minimum baseline distance, i.e. the No.2 baseline distance is 1.44mm and the NO.3 baseline distance is 2.16mm. We propose to use Si₃N₄/SiO₂ waveguides with 150nm Si₃N₄ as the waveguide core providing around 30% refractive index difference percentage ($\Delta n\%$) which is orders of magnitude higher than the previous silica waveguide. This Si₃N₄ based high index contrast waveguide platform would further minimize the PIC size and power consumption when maintaining the comparable optical loss to the silica waveguide platform. When light couples into this Si₃N₄ PIC, it travels through a section of path-length-matched waveguides starting from the corresponding baselines to maintain the in-phase condition and spatial coherence. These path-length-matched waveguides are marked with different colors for different baselines. We do encounter the unavoidable waveguide crossings routing all 12 baselines. And we plan to develop the multilayer coupling technology within Si₃N₄ platform employing a thinner 50nm Si₃N₄ layer as a transition layer to avoid the waveguide crossings. The relevant Si₃N₄ designs with simulations of waveguide mode, mode size, mode refractive index and bending loss are presented in the following section. The two waveguides coming from the paired lenslets meet at a heater assisted MMI in order to generate the complex visibility interference fringes. In this PIC design, we move the interferometer ahead of the demux to decrease the number of interferometers needed for each baseline from 18 to 1 (we have total 18 wavelength channels to meet the Nyquist sampling rate). The MMI structure has broadband interference capability comparing to a directional-coupler type of interferometer given that we use the light covering a 1200nm ~ 1600nm wavelength band. We will perform beam propagation method based simulation for MMI structure covering the desired wavelength band. The interfered lights

coming out of the MMI is demultiplexed through AWG into 18 different wavelength channels covering the 1200nm ~ 1600nm band. We use the AWG structure to achieve the proposed demultiplexing capability since it has excellent wavelength filtering performance and it could utilize both star couplers as demux outputs reducing the number of AWGs needed by a factor of two. The waveguides in the arrayed arms of AWGs increases linearly to introduce a linear progression of phase. The induced phase in the arrayed waveguide arms varies with the wavelength because of the total length difference and the wavelength dependence of propagation constant. This phase delay for different wavelength channels will induce the phase tilt at the output star-coupler. Thus different wavelength channels will constructively interfere with the output mode profile at different locations at the output star-coupler. Phase errors generated along the propagation in the AWGs should be mitigated in order to lower the crosstalk of adjacent wavelength channels. The lights coming from the same wavelength channel in the same AWG but from different star couplers are guided towards to end of the PIC shown in different waveguide colors (red, green and blue). The paired waveguides from the same AWG could be further guided into a balanced coherent detection system to minimize the constant noise. The linear detector arrays are connected to the end of the PIC to digitize both the amplitude and phase of the complex visibility fringes. We will perform DSP to mitigate the extra noise generated within the whole system.

3.2.2. PIC design and layout

Figure 3.2.2 shows the front view of PICs' baselines configurations. We include total 12 baselines in the PIC design. In the low resolution case (shown in Figure 3.2.2 (a)), the shortest baseline is 0.72mm whereas the longest baseline is 20.88mm. The distances of baselines in between are integer times of the shortest baseline distance. 12 baselines as a whole could be further mapped into the u-v spatial frequency domain to represent the spatial frequency sampling employed upon the received image. By having 20.88mm as the longest baseline we could successfully fabricate the chip utilizing 248nm projection lithography technology in Marvel Nanolab in UC Berkeley. And we also include a high-resolution baseline layouts in Figure 3.2.2 (b) where the corresponding baseline distance is roughly 4 times of that in the low-resolution layout.

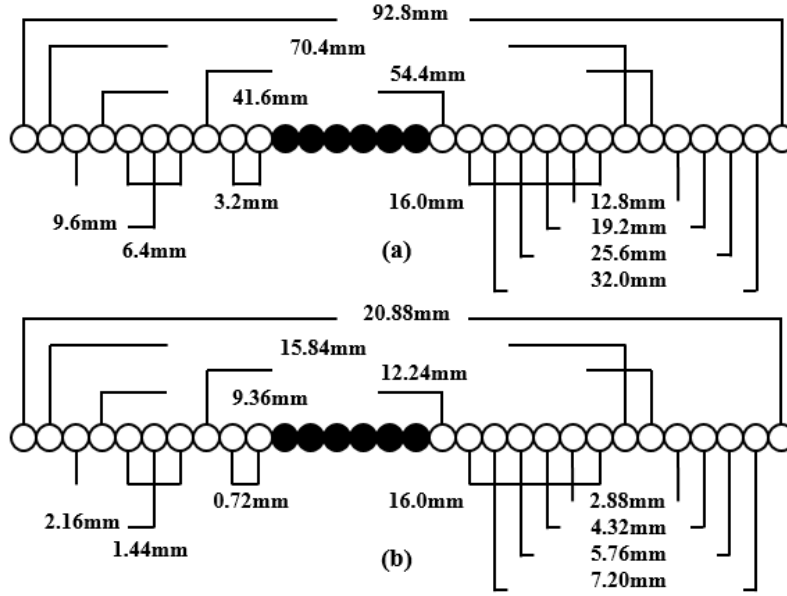


Figure 3.2.2 Front view of (a) a low image resolution PIC baseline arrangement (b) a high resolution PIC baseline arrangement.

This increased baseline distances could help to enhance the resolution of the image by a factor of 4. Because we propose the longest baseline to be 92.88mm (close to a 4" wafer diameter), we'd have to use contact lithography on a 6" wafer to realize this high-resolution PIC. The smallest feature resolved by our current contact aligner is around $1\mu\text{m}$, 4 times larger than the minimum feature generated by projection lithography, which could possibly introduce lateral misalignment and extra coupling loss. The interferometer baseline layout has been modified to enable a PIC design that is simpler with no waveguide crossovers. The new interferometer baseline description is shown in Figure 3.2.3. We also summarize the AWGs wavelength channel information into Figure 3.2.4 where the stripes with different colors and widths represent the 18 different wavelength channels used for imaging.

Baseline #	Baseline [mm]	NDOF	Spectral Bin #'s
1	0.72	1.0	1,18
2	1.44	2.0	1,9,18
3	2.16	2.0	2,7,12,17
4	2.88	3.0	1,5,9,13,17
5	3.60	4.0	1,4,7,10,13
6	4.32	4.0	2,5,8,11
7	5.76	6.0	2,4,6,8,10,12,14,16,18
8	7.20	7.0	1,3,5,7,9,11,13,15
9	9.36	9.0	1,3,5,7,9,11,13,15,17
10	12.24	11.0	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18
11	15.84	15.0	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18
12	20.88	19.0	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18

Spectral Bin #	Center Frequency [THz]	Spectral Width [THz]	Center Wavelength [nm]	Spectral Width [nm]
1	245	3.30	1223	16.5
2	242	3.30	1240	16.9
3	238	3.30	1257	17.4
4	235	3.30	1275	17.9
5	232	3.30	1293	18.4
6	229	3.30	1311	18.9
7	225	3.30	1331	19.5
8	222	3.30	1350	20.1
9	219	3.30	1371	20.7
10	215	3.30	1392	21.3
11	212	3.30	1413	22.0
12	209	3.30	1436	22.7
13	206	3.30	1459	23.4
14	202	3.30	1483	24.2
15	199	3.30	1507	25.0
16	196	3.30	1533	25.8
17	192	3.30	1559	26.7
18	189	3.30	1586	27.6

Figure 3.2.3 Updated description of the low-resolution PIC interferometer baselines and the spectral binning per baseline

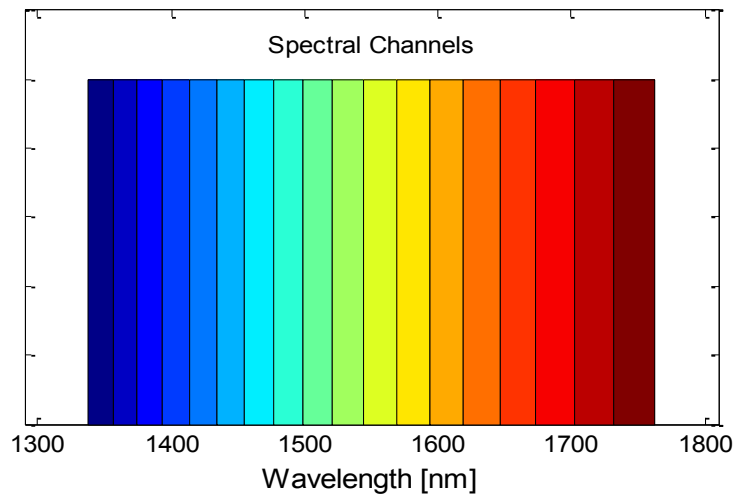


Figure 3.2.4 AWG wavelength channels working as demultiplexer

Figure 3.2.5 illustrates the 3.3THz, 18 channel, side-input AWGs we design on the 150nm Si₃N₄ waveguide platform with approximate 2.7mm × 3mm device size. We plan to finish the layouts for both MMIs and AWGs by iterating the design, fabrication and characterization steps in order to improve the device performance.

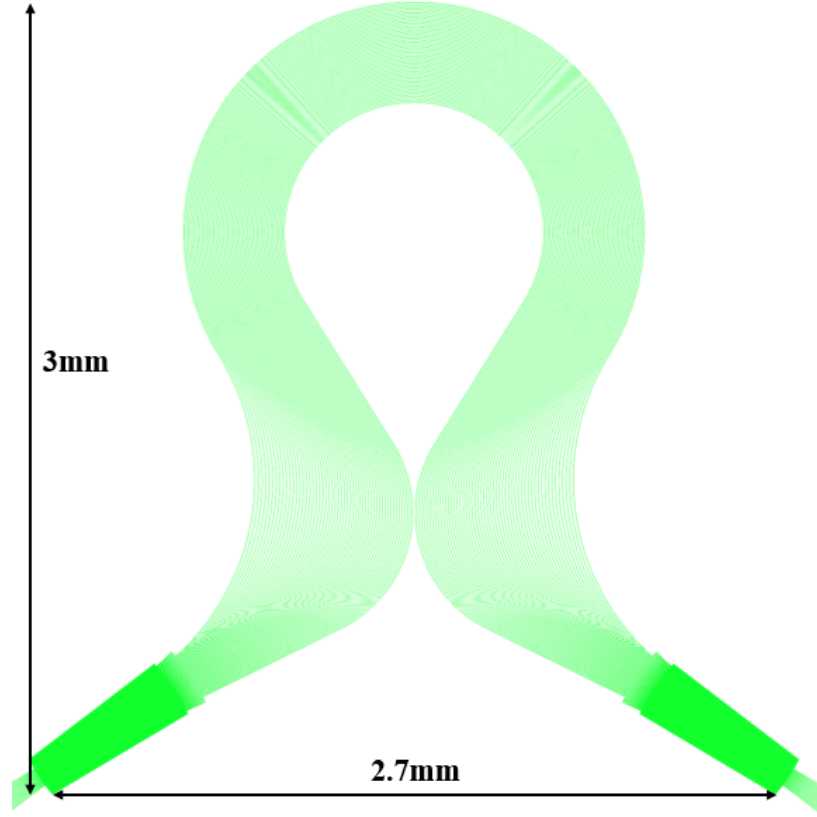


Figure 3.2.5 Representative 18 channel Si₃N₄ AWG layout

The layout of the high-resolution PIC is shown in Figure 3.2.6 (a), with the new low-resolution PIC design implemented. The high-resolution PIC also has five layers with layer 2 split into two parts to accommodate the additional long baseline fan-in. The design can be scaled to obtain finer resolution with a smaller field of view, by simply scaling the pupil-plane interferometer geometry. In practice, this is accomplished by adding a fan-in waveguide chip (to accommodate longer interferometer baselines) on the input side of the PIC and using larger lenslets to couple light into the PIC. Figure 3.2.6 (a) shows the layout for a high-resolution device based on adding a fan-in chip to an existing low-resolution PIC design.

Figure 3.2.6 (b) shows the layout of the low-resolution PIC. It consists of five layers, including three layers containing waveguides. The heaters provide the ability to control the phase of the fringe and can be used to scan through a fringe temporally. There are total of 12 baselines, with the minimum baseline of 0.72 mm and maximum baseline of 20.88 mm. The arrayed waveguide grating (AWG) has 36 outputs, 2 output for 18 wavelength channels. All 12 baselines are using the exact same AWG and MMI (multi-mode interference) coupler design. The two components from the same baseline share the same AWG, one using north input and the other

one using south input. Since they use the same array arms, the wavelength difference between beams is reduced to minimum.

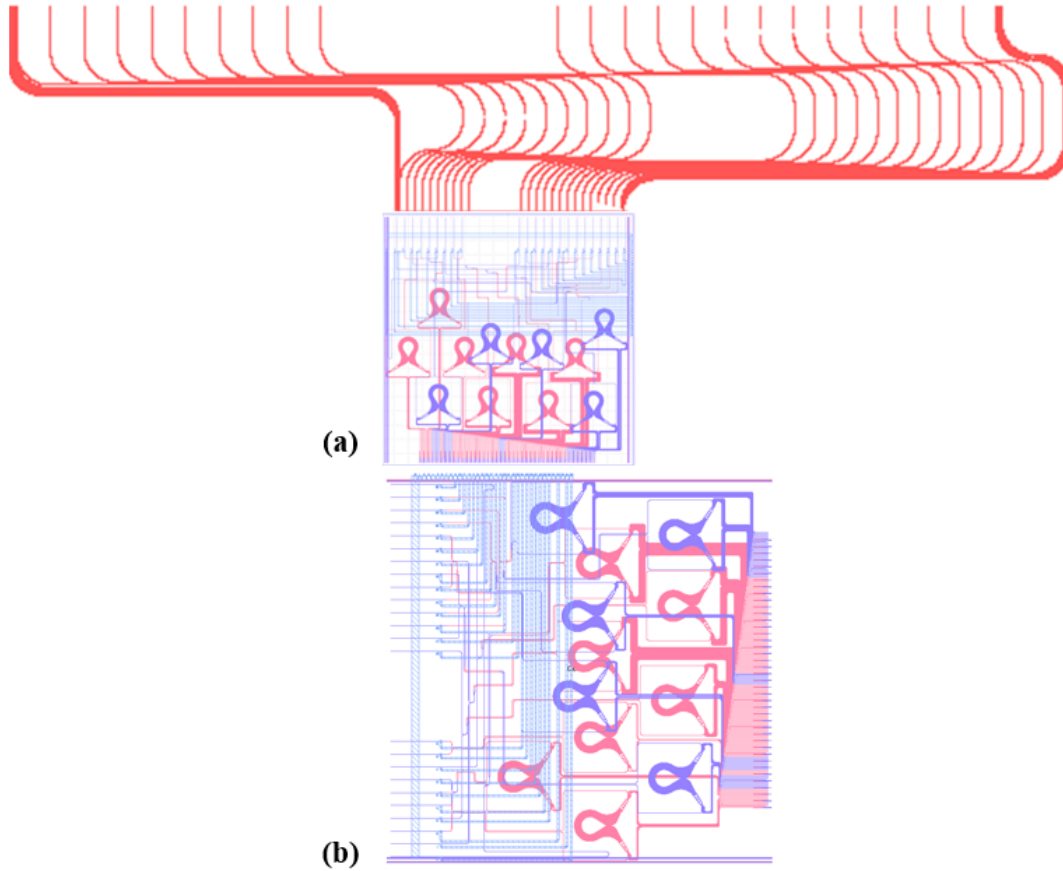


Figure 3.2.6 (a) Mask layout for high-resolution PIC (b) Mask layout for low-resolution PIC

The maximum exposure area of the photolithography tool, in this case $22\text{ mm} \times 22\text{ mm}$, limits the size of the SPIDER Zoom low-resolution device, which holds twelve AWGs and MMIs. The three-layer waveguide structure reduces the waveguide crossing to one crossing per channel and provides enough area to place the AWGs. The layout process is as follows: 1) put 12 AWGs in a 4×3 matrix, then assign them to each of the 150 nm waveguide layers so that AWGs from the same layer has enough spacing; 2) route each baseline channel to the closest AWG using Manhattan routing method; 3) change the layer of baselines and AWGs and add necessary layer-to-layer coupler so that overall loss from crossing and layer change is reduced to minimum; 4) add metal heaters on 1500 μm -long layer-3 waveguide, connecting the heaters to metal pads on the edge of the chip for future wire-bonding.

3.2.3. PIC Characterization

For initial testing, we use a broadband light source and launch transverse electric (TE)-mode light into the device under test from a lens fiber. At the output end, a lens fiber captures and sends the light to an OSA (optical spectrum analyzer). We scan the spectrum between 1200 nm and 1600 nm for all the inputs and all the outputs. We measure the heater resistance around 170Ω for all 24 inputs. The electrode resistance range from 10Ω to 40Ω , depending on the

length of the electrode. From single-layer testing, we find that the energy required for 2π phase change of the heaters is around 320 mW. For any given input/output part, the total transmission is the combination of 2x2 MMI transmission and AWG transmission. We measure the 1550 nm channel from two different wafers and two dies from each wafer. Figure 3.2.7 shows representative optical throughput measurements normalized to the straight through PIC waveguides. Figure 3.2.8 shows fringe measurements for a representative interferometer channel.

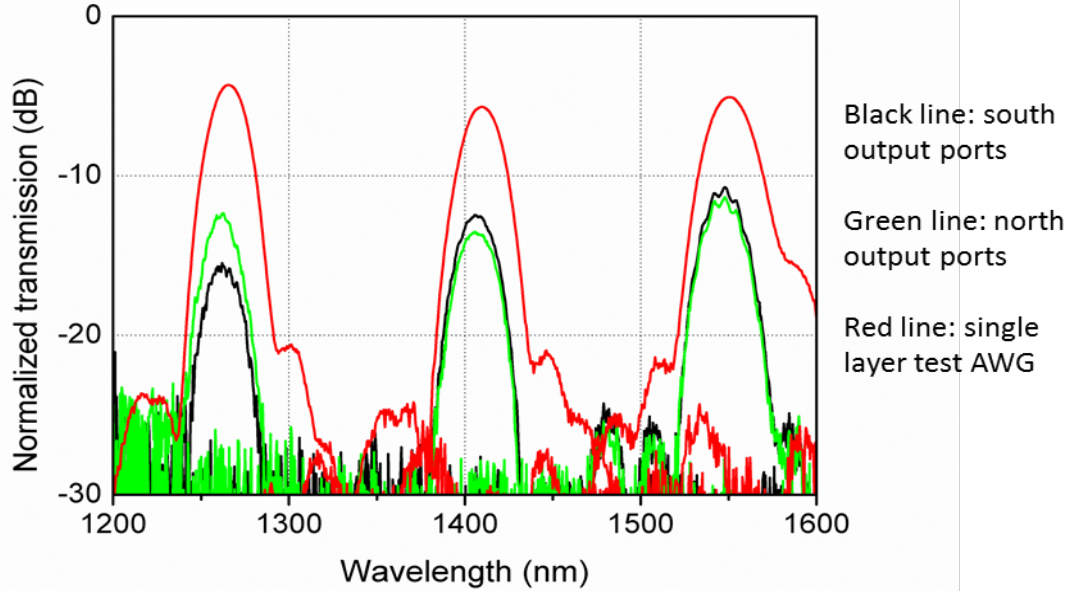


Figure 3.2.7 Low-resolution PIC optical throughput measurements

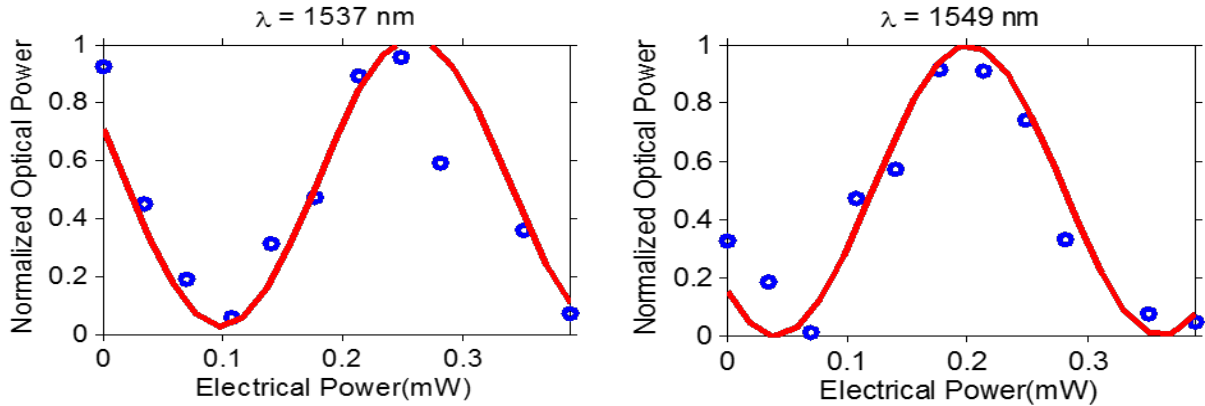


Figure 3.2.8 Low-resolution PIC interferometer heater response fringe measurements

Figure 3.2.9 shows the fabricated high-resolution PIC. We aligned the lensed fiber to the waveguide by coupling red light into the waveguide. We measured the transmission of PIC using the OSA. Figure 3.2.10 shows the measured transmission. The high-resolution device shows the matched transmission band with an excess loss of 6 dB compared with previous low-resolution devices.

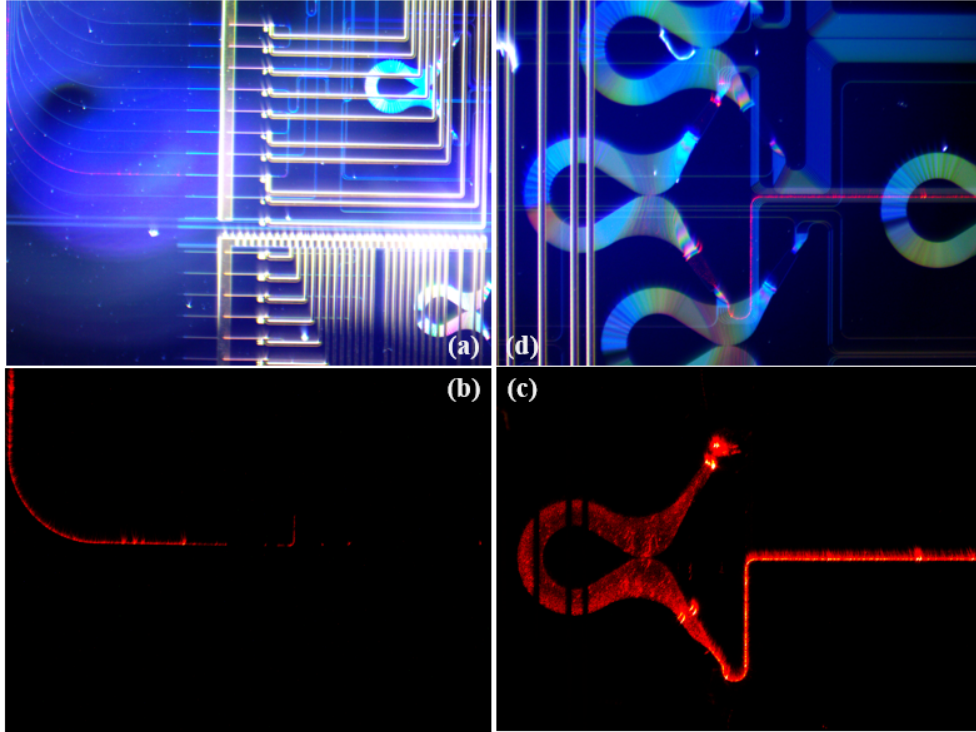


Figure 3.2.9 Red laser light coupled into (a) PIC input, bright field (b) PIC input, dark field (c) PIC output, bright field (d) PIC output, dark field

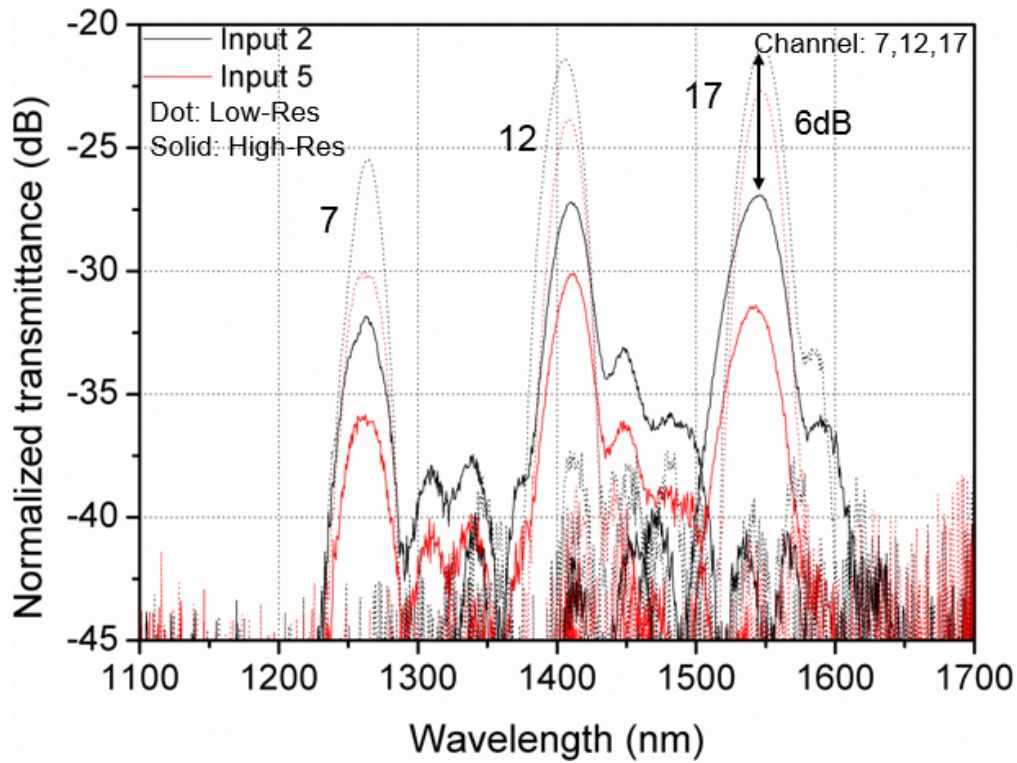


Figure 3.2.10 High-resolution PIC optical throughput results (solid line) referenced to low-resolution PIC optical throughput results (dashed line)

3.2.4. Imaging Experiment

Figure 3.2.11 shows the stage that holds the SPIDER PIC for the imaging measurement. The $22\text{ mm} \times 22\text{ mm}$ PIC is sitting on top of a stainless steel block for heat dissipation and mechanical support. The white round holder on the left holds the lenslet array. It is capable of tuning the lenslet array in x , y , z and tilt direction. The black tube on the right side of PIC is a set of 1:1 imaging optics, projecting the PIC outputs to a camera. The camera is a 640×512 detector array with $25\text{ }\mu\text{m}$ pixel pitch. Figure 3.2.12 (a) shows the setup for the input light source. The light beam coming out of a fiber collimator goes through a pair of mirrors before arriving at the lenslet array and PIC that's in Figure 3.2.11. One of the two mirrors is attached to a rotating motor. When that mirror rotates, we can simulate the light source moving and measure the fringe from PIC outputs.

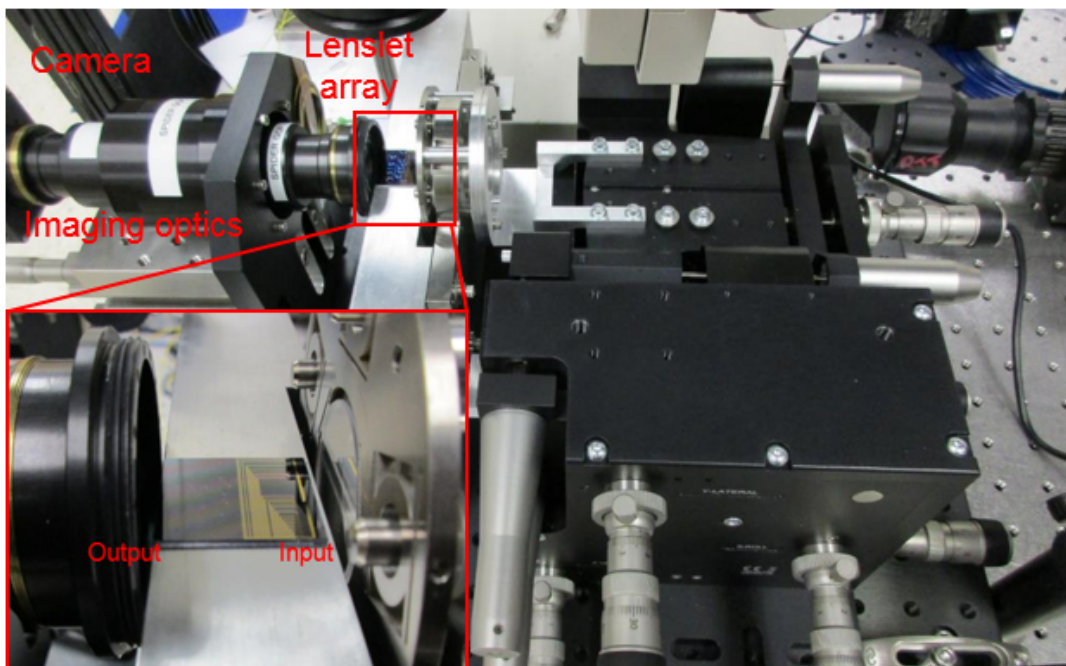


Figure 3.2.11 Photo of Fringe measurement setup

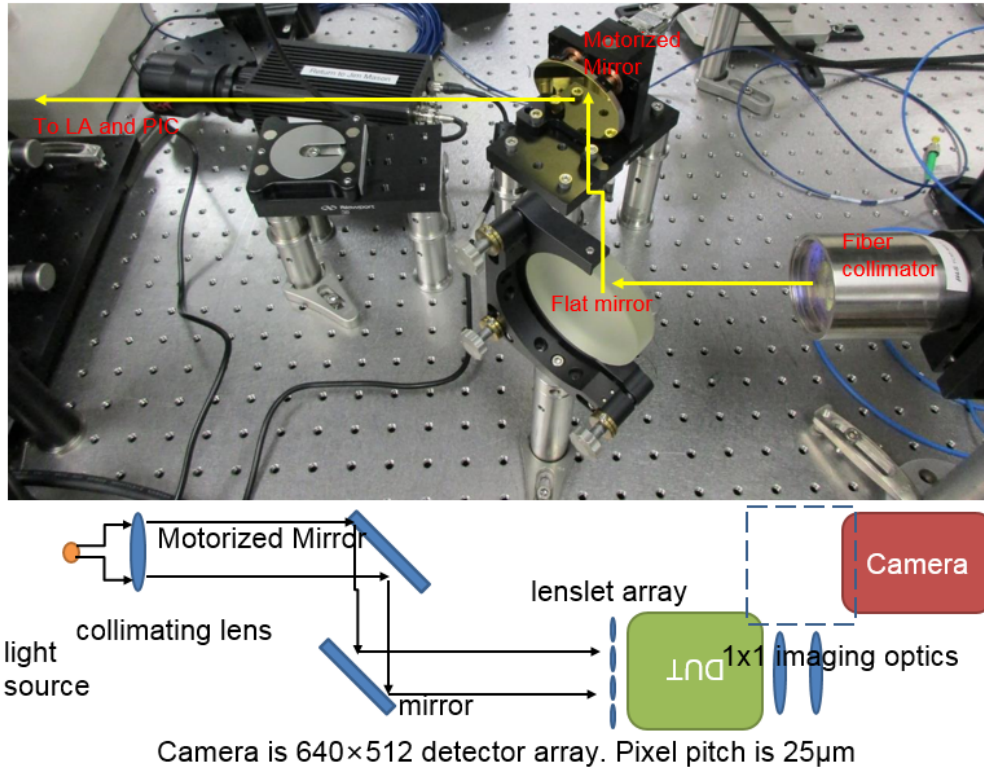


Figure 3.2.12 Photo and Sketch for SPIDER imaging setup

Figure 3.2.13 shows the image received at the camera. In this case, we launch broadband ASE light to illuminate all outputs. The inset of **Error! Reference source not found.** shows zoom-in picture focusing on the PIC outputs. Since the PIC outputs have a pitch of 75 μm, its 1×1 image on the camera shows up every 3 pixels. By taking the intensity data from the camera while turning the motorized mirror, we can generate fringe data. Figure 3.2.14 shows some examples of the fringe data. The first three fast varying fringes are generated from large baselines. The other slow varying fringes are generated from small baselines.

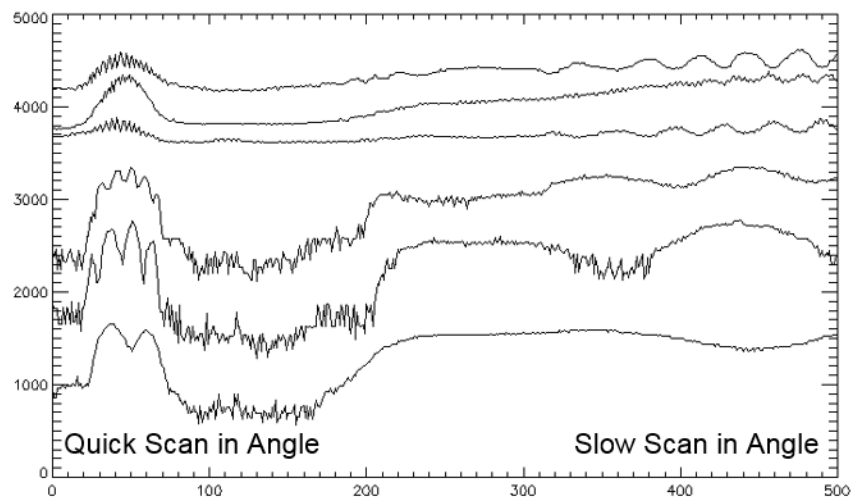


Figure 3.2.13 Camera received imaging output through baseline 3,4,9,12 at different scan angles

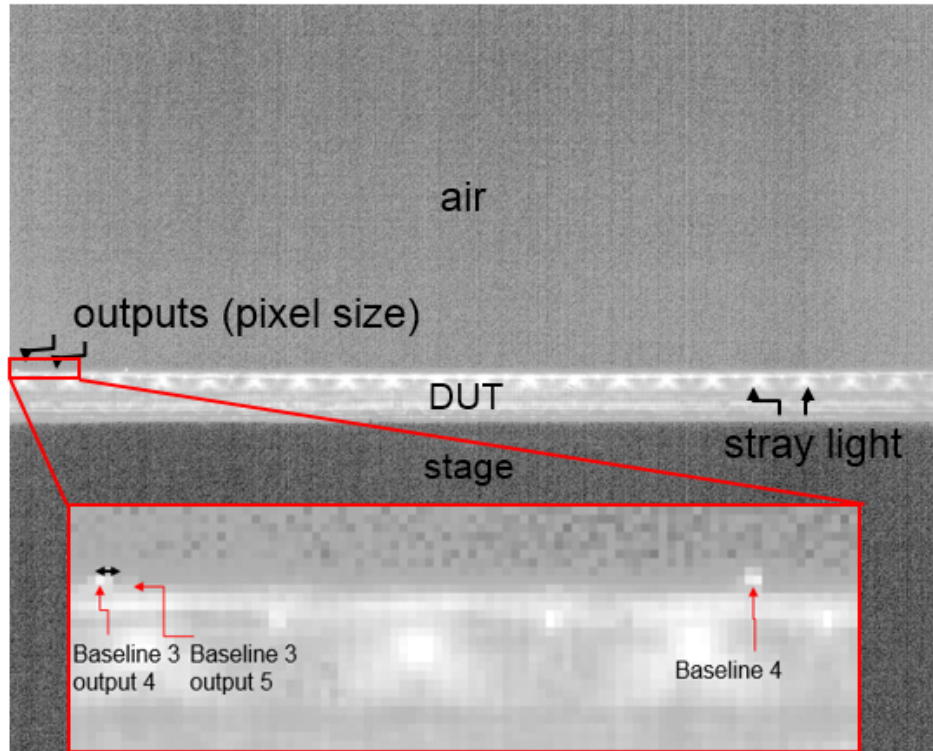


Figure 3.2.14 Image generated from low-resolution PIC using ASE source

3.3. Signal-to-Noise Ratio Analysis

3.3.1. The Conventional Panchromatic Imager Signal-to-Noise Ratio

In this section, we will first review the signal-to-noise ratio (SNR) in a conventional panchromatic imager, and we will provide the SNR of the Segmented Planar Imaging Detector for Electro-optical Reconnaissance (SPIDER) imager.

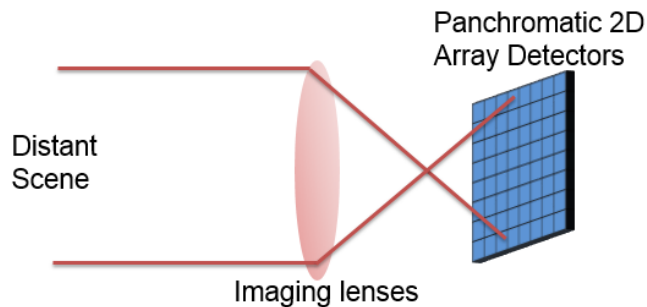


Figure 3.3.1 Schematic of conventional panchromatic imager

A panchromatic imager is composed of a 2D array of single channel detectors that are sensitive to light within a broad wavelength range. Figure 3.3.1 shows a schematic of the imager. The physical quantity being measured is the apparent brightness of the targets. The resulting image resembles a grayscale photo, while the spectral information of the target is lost.

We assume the noise of a detector in the 2D array is a combination of independent zero-mean shot noise and Gaussian distributed detector read noise. The detector shot noise is proportional to the signal level of the detector.

$$\sigma_{pan}^2(x_{m,n}) = \kappa P_{pan}(x_{m,n}) + \sigma_0^2 \quad (1)$$

Here $\sigma_{pan}^2(x_{m,n})$ is the total noise, $P_{pan}(x_{m,n})$ is the signal level for pixel (m,n) , and σ_0^2 is the standard deviation of the detector read noise. We can calculate the signal level $P_{pan}(x_{m,n})$ from the source intensity and spectrum distribution,

$$P_{pan}(x_{m,n}) = GSD^2 \tau \frac{\pi D^2}{4R^2} \iint \eta(\lambda) \frac{\lambda}{hc} L_\lambda(x', \lambda) h_\lambda(x_{m,n} - x', \lambda) dx' d\lambda \quad (2)$$

Here GSD is the detector pixel grid projecting onto the object plane, D is the receiver aperture diameter, $\eta(\lambda)$ is the efficiency factor, and $h_\lambda(x, \lambda)$ is the system impulse response.

The discrete Fourier transform (DFT) of the image, $G(u_{p,q})$, is given by

$$G(u_{p,q}) = \frac{P_{tot}}{\sqrt{MN}} \int S(\lambda) W(u_{p,q}, \lambda) H_\lambda(u_{p,q}, \lambda) d\lambda \quad (3)$$

$S(\lambda)$ is the normalized spectral weighting term, $W(u, \lambda)$ is the 2D spatial Fourier transform of the object spectral radiance distribution, and $H_\lambda(u, \lambda)$ is the system transfer function. For the total number of image photoelectrons P_{tot} , we have

$$P_{tot} = \sum_{(m,n)} P_{pan}(x_{m,n}) \approx \iint \frac{P_{pan}(x)}{GSD^2} dx \quad (4)$$

Analyzing the noise in this system, we assume that the noise in each measurement is zero-mean and independent from other measurements. Since the noise in each pixel has a white spectrum and the total power is evenly distributed among all pixels, we can write the noise on each pixel as

$$\Phi_{noise}(u_{m,n}) = \frac{P_{tot}}{MN} + \sigma_0^2 \quad (5)$$

Then, we conclude that the Fourier domain SNR for conventional panchromatic imager is the ratio between the DFT of the image and the noise

$$SNR_{pan}(u_{p,q}) = \frac{|G(u_{p,q})|}{\sqrt{\Phi_{noise}(u_{p,q})}} = \frac{P_{tot}}{\sqrt{P_{tot} + MN\sigma_0^2}} \left| \int S(\lambda) W(u_{p,q}, \lambda) H_\lambda(u_{p,q}, \lambda) d\lambda \right| \quad (6)$$

3.3.2. The SPIDER Imager Signal-to-Noise Ratio

This section provides the SNR of the SPIDER imager. The SPIDER imager contains N interferometer baselines. For each baseline, the target light is split into K spectral channels. The imager measures fringe visibility on selected spectral channel of the baselines. Through Van Cittert-Zernike theorem, we can convert the fringe visibility information to target optical intensity information using Fourier transform.

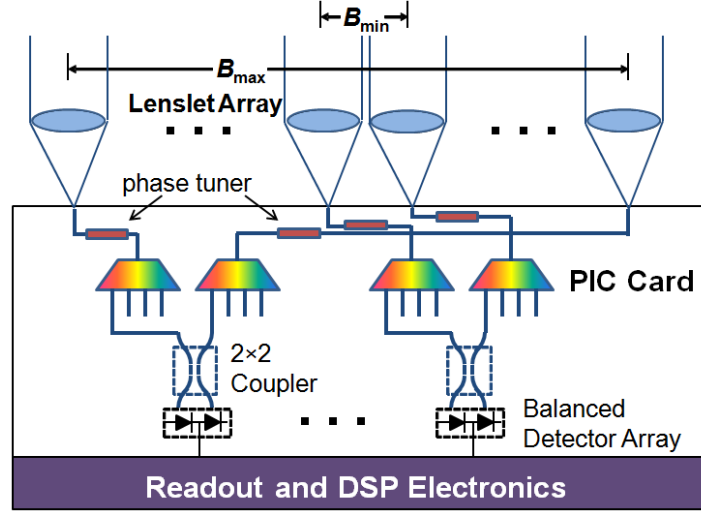


Figure 3.3.2 Schematic figure of the optical path for the visibility measurement of a single spectral channel of two interferometer baselines.

Figure 3.3.2 shows the schematic figure of the SPIDER device that can measure fringe visibility for a single spectral channel of two different interferometer baselines ($B_{\min}$, $B_{\max}$). Starting from the top, the lenslets couple broadband light from the distant target into waveguides on a photonic integrated circuit. Arrayed waveguide gratings split the coupled light into K spectral channels, which each channel connects to a 2×2 directional coupler. Detector pairs measure the two beams of light from the same spectral band of a given baseline after they interfere at the 2×2 directional coupler. Stepping the phase tuner change the relative phase of the interfered light, and we measure the optical power at detectors to obtain fringe visibility.

A SPIDER system measures the normalized cross-spectral density of the scene $W_\rho(u, \lambda)$, which represents the spatial coherence between two points separated by B in the aperture plane at each wavelength. $W_\rho(u, \lambda)$ links to the intensity distribution $L_\lambda(x, \lambda)$ through a spatial Fourier transform (Van Cittert-Zernike theorem)

$$W_\rho(u, \lambda) = \frac{\iint \rho(x, \lambda) L_\lambda(x, \lambda) \exp(-i2\pi ux) dx}{\iint \rho(x, \lambda) L_\lambda(x, \lambda) dx} \quad (7)$$

$$u = \frac{B}{\lambda R}$$

Here u is the spatial frequency coordinate, B is the interferometer baseline spacing and R is the target distance. $P(x, \lambda)$ is the lenslet/waveguide coupling efficiency projected onto the object plane. The SPIDER device measures the fringe visibility of enough baselines, and then it constructs the scene intensity information through inverse Fourier transform.

Assuming the coupling efficiency and optical throughput to the detector is identical for all baselines and spectral channels, the two signal ($l = 0, 1$) from the two output ports for the j -th baseline and k -th spectral channel can be written as

$$P_l(B_j, \lambda_k) = P_0(\lambda_k) \left\{ 1 + \text{Re} \left[e^{il\pi} W_\rho \left(\frac{B_j}{\lambda_k R}, \lambda_k \right) \right] \right\} \quad (8)$$

Here $P_0(\lambda)$ is the detector signal corresponding to zero fringe visibility. It is related to the object spectral radiance by radiometric equation

$$P_0(\lambda) = \eta(\lambda) \frac{\lambda}{hc} \tau \frac{\pi D_{lenslet}^2}{4R^2} \Delta\lambda \iint \rho(x, \lambda) L_\lambda(x, \lambda) dx \quad (9)$$

Here $\eta(\lambda)$ is an efficiency factor that includes optical losses and detector quantum efficiency, τ is the detector integration time, $D_{lenslet}$ is the lenslet aperture diameter, and $\Delta\lambda$ is the bandwidth of each spectral channel. Then, we can write the fringe visibility as

$$W_\rho(u_{j,k}, \lambda_k) = \frac{1}{2} \left(\frac{P_{1\max} - P_{1\min}}{P_{1\max} + P_{1\min}} + \frac{P_{2\max} - P_{2\min}}{P_{2\max} + P_{2\min}} \right) \quad (10)$$

Similar to the panchromatic imager, if we assume the measured noise is a combination of Gaussian distributed detector noise and Poisson distributed shot noise, we can write the noise variance of each measurement as

$$\sigma_l^2(B_j, \lambda_k) = \kappa P_l(B_j, \lambda_k) + \sigma_0^2 \quad (11)$$

where σ_0 is the standard deviation of the detector read noise.

Applying standard propagation of error rule to the fringe visibility $W_\rho(u, \lambda)$ gives us the noise term. In most cases, we can assume the visibility is less than a few percent to simplify the equation.

$$\Phi_{noise}(u_{j,k}, \lambda_k) = \frac{P_0(\lambda_k) + \sigma_0^2}{P_0^2(\lambda_k)} - \frac{P_0(\lambda_k) - \sigma_0^2}{4P_0^2(\lambda_k)} |W_\rho(u_{j,k}, \lambda_k)|^2 \approx \frac{P_0(\lambda_k) + \sigma_0^2}{P_0^2(\lambda_k)} \quad (12)$$

The signal-to-noise ratio is the ratio of the fringe visibility amplitude to the square root of the noise power

$$SNR_{SPIDER}(u_{j,k}) = \frac{|W_\rho(u_{j,k}, \lambda_k)|}{\sqrt{\Phi_{noise}(u_{j,k}, \lambda_k)}} \approx \frac{P_0(\lambda_k)}{\sqrt{P_0(\lambda_k) + \sigma_0^2}} |W_\rho(u_{j,k}, \lambda_k)| \quad (13)$$

Intuitively, total SNR is the product raw data SNR and the fringe visibility.

3.3.3. The SNR Comparison of the Two Imagers

We have discussed the SNR of a SPIDER imager and that of a conventional panchromatic imager. To directly compare the two SNRs, we will make three assumptions.

- The object is unresolved by the individual SPIDER lenslet apertures. This means the lenslet coupling efficiency $\rho(x, \lambda)$ is a constant in the x and λ range we are measuring. So that

$$W_\rho(u, \lambda) \approx W(u, \lambda) \quad (14)$$

- Gray world approximation: the spectral distribution of light is identical for each point on the object. The normalized cross-spectral density of the scene has

$$W(u, \lambda) = W(u) \quad (15)$$

- Both systems operate in the shot noise limit.

$$\sigma_0^2 \ll \kappa P_0 \text{ or } \kappa P_{tot} \quad (16)$$

Under above three assumptions, we rewrite the SNR for both systems:

$$\begin{aligned} SNR_{pan}(u_{p,q}) &\approx \sqrt{P_{tot}} |H_{pan}(u_{p,q})| W(u_{p,q}) \\ SNR_{SPIDER}(u_{j,k}) &\approx \sqrt{P_0(\lambda_k)} |W(u_{j,k})| \end{aligned} \quad (17)$$

Here $H_{pan}(u) = \int S(\lambda) H_\lambda(u, \lambda) d\lambda$ is the spectrally weighted panchromatic imager transfer function. As a result, we can compare the SNR at the same spatial frequency for both systems

$$\frac{SNR_{pan}(u_{j,k})}{SNR_{SPIDER}(u_{j,k})} \approx \frac{\sqrt{P_{tot}}}{\sqrt{P_0(\lambda_k)}} |H_{pan}(u_{p,q})| \quad (18)$$

The first part is the square root of the ratio in photoelectron signal levels. The second part is the transfer function of the panchromatic imager. The photoelectron signal ratio can be estimated as

$$\sqrt{\frac{P_{tot}}{P_0(\lambda_k)}} = \sqrt{\frac{2D^2}{D_{lenslet}^2 S(\lambda) \Delta \lambda}} \quad (19)$$

To do a fair comparison, we assume both systems is similar in size, so the aperture diameter D of the panchromatic imager is about equal to the longest interferometer baseline. If the adjacent lenslets in SPIDER system are right next to each other (for maximum coupling efficiency), the parameter α is approximately equal to two times the number of baselines.

$$D = B_{\max} = \alpha D_{lenslet} \quad (20)$$

The spectral factor $S(\lambda) \Delta \lambda$ represent the portion of light in k -th spectral channel. Assume an ideal AWG design that is lossless and the light is evenly divided among K total spectral channels, we get

$$S(\lambda) \Delta \lambda \approx \frac{1}{K} \quad (21)$$

In our silicon SPIDER ZOOM device, α is equal to 12 and K is equal to 18. If we design for maximum coupling efficiency,

$$\sqrt{\frac{P_{tot}}{P_0(\lambda_k)}} \approx \sqrt{2\alpha^2 K} \approx 72 \quad (22)$$

In summary, at the lowest spatial frequency, the modulation transfer function(MTF) $|H_{pan}(u)|$ is close to 1, so the SNR of a conventional imager is ~ 72 times better than that of a SPIDER imager. Near the cutoff spatial frequency, the MTF $|H_{pan}(u)| \approx 0.01 \sim 0.02$, the two approaches will have similar SNR.

3.3.4. A Simulation Example

A computer simulation was performed to illustrate the SPIDER concept. The simulation parameters are shown in Table 1. The SPIDER system is composed of a set of photonic integrated circuit (PIC) cards on 6 inch wafers. Lenslets couple light into the waveguides along the edge of each PIC card. There are 14 lenslets per PIC, and they are paired up to form 7 interferometer baselines along one dimension. 37 separate PIC cards are arranged in a radial pattern to for a two dimensional interferometer array with $J = 7 \times 37 = 259$ different baselines B_j . Spatial frequency coverage is enhanced by dividing the visible waveband into $K = 10$ spectral channels. Figure 3.3.3(b) shows the resulting $J \times K = 2590$ Fourier samples $u_{j,k}$. Because of the wavelength scaling of the sampling locations, the sampling is denser at low spatial frequencies.

Table 1. Simulation Parameters.

Parameter	Value
Waveband	$\lambda = 0.5\text{-}0.9\ \mu\text{m}$
Object distance	$R = 60\ \text{km}$
Longest baseline	$B_{\text{max}} = 120\ \text{mm}$
Lenslet diameter	$D_{\text{lenslet}} = 5\ \text{mm}$
Lenslets per PIC Card	14
PIC cards	37
Number of spectral channels	$K = 10\ (\Delta\lambda = 40\ \text{nm})$
Detector quantum efficiency	$\eta = 0.7\ \text{e}^-/\text{photon}$
Detector read noise	$\sigma_0 = 8\ \text{e}^-$
Integration time	$\tau = 1\ \text{sec}$

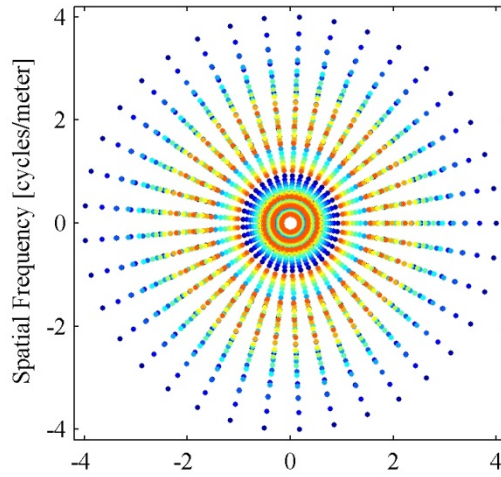


Figure 3.3.3 Fourier samples for the example SPIDER system. The sample points are colored according to wavelength, with red representing the longest wavelength and blue representing the shortest wavelength.

The simulation used a multispectral model of a generic Lockheed Martin A2100 satellite scaled to have a width of 10 m across as the object. This model was created using the Digital Imaging and Remote Sensing Image Generation (DIRSIG) software. Figure 3.3.4(a) is a panchromatic view of the satellite model. The model represents the object spectral radiance distribution $L_\lambda(\mathbf{x}, \lambda)$ under passive solar illumination. Figure 3.3.4(b) shows normalized spectra for various points in the scene. The difference between these curves results from the detailed material properties for the various satellite components. The average or “gray world” spectrum for the scene is also shown in Figure 3.3.4(b). The gray world spectrum matches the spectrum for the satellite solar panels closely, because these are the brightest and largest portions of the object. While this is not a true gray world scene, we invoke the gray world approximation to reconstruct the SPIDER image below.

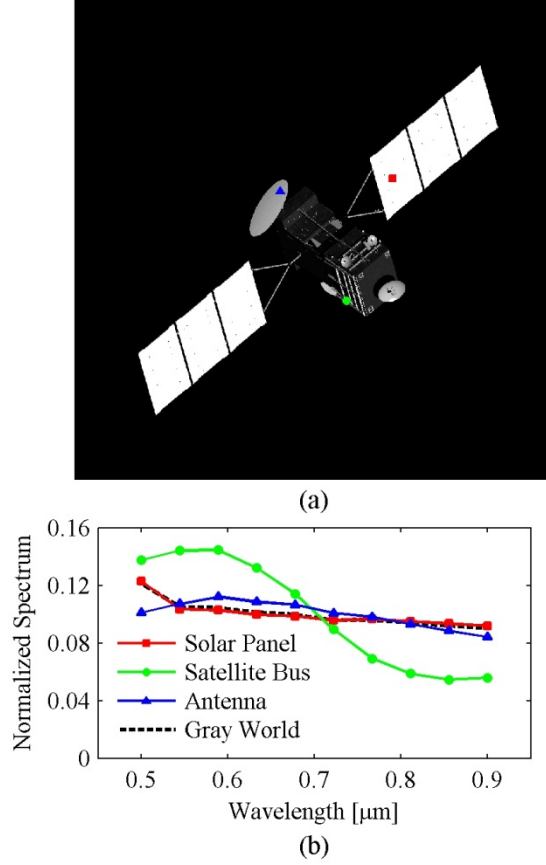


Figure 3.3.4 Object data used for the simulation: (a) panchromatic view of the scene; and (b) spectral plots for various points in the scene along with the average “gray world” spectrum for the object.

Figure 3.3.5 shows the SPIDER simulation results. Figure 3.3.5(b) shows the visibility signal and noise levels as a function of radial spatial frequency. The raw signal levels for the quadrature detection measurements varies across the spectral channels, but were all in the range $P_0(\lambda_k) = 2.7\text{-}3.2 \times 10^4 \text{ e}^-$. Using these values, the visibility noise level should be approximately

$\sqrt{\Phi_{\text{noise}}(\mathbf{u}_{j,k}, \lambda_k)} \approx 5.6\text{-}6.1 \times 10^{-3}$. These values are in agreement with the green curve of Figure

3.3.5(b). From the plot, it can be seen the SNR of the visibility data approaches unity near a spatial frequency of $|\mathbf{u}| \approx 3.6 \text{ cycles/m}$. Figure 3.3.5(a) shows the image reconstruction result. There is some high spatial frequency noise, but the image looks quite good. Notice that the outer edges of the solar panels are shaded just a bit. This is a result of the waveguide coupling term $\rho(\mathbf{x}, \lambda)$ that basically apodizes the image. For the simulation, this term was approximated as a 2D Gaussian with a width equal to the object-plane resolvable spot size of the SPIDER lenlets, *i.e.*,

$$\rho(\mathbf{x}, \lambda) \approx \exp \left[-\frac{1}{2} \left(\frac{D_{\text{lenlet}}}{0.44\lambda R} \right)^2 |\mathbf{x}|^2 \right]. \quad (23)$$

The full width at half maximum of $\rho(\mathbf{x}, \lambda)$ varies between 6.0 m for the shortest wavelength and 10.8 m for the longest wavelength. For comparison, the DIRSIG object scene has a width of 10 m. The reconstruction algorithm is based on the gray world approximation and does not account

for the spectral variation in $\rho(x, \lambda)$. It reconstructs an image with a net apodization that is equivalent to a weighted sum of $\rho(x, \lambda)$ across the various spectral channels.

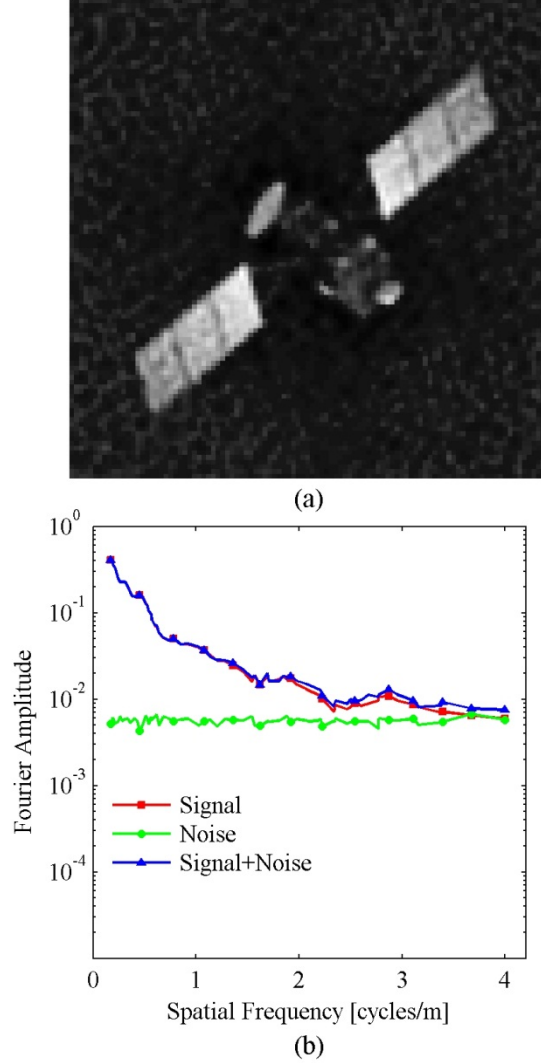


Figure 3.3.5 SPIDER simulation results: (a) reconstructed image; and (b) plot of the visibility signal and noise levels vs. radial spatial frequency.

Figure 3.3.6 shows simulation results for a conventional panchromatic imaging system for comparison with the SPIDER system. The aperture diameter for this simulation was set to $D = \max(B_j) = 120$ mm to get approximately the same resolution as the SPIDER system. This is $\alpha = 24$ times wider than the SPIDER lenslets. The total number of photoelectrons in the image was $P_{\text{tot}} = 5.1 \times 10^8$ e⁻. This is about 45% greater than would be expected from the approximation which ignores the impact of $\rho(x, \lambda)$ on the SPIDER signal levels. Thus, we expect the conventional image SNR to be approximately

$$\sqrt{\frac{P_{\text{tot}}}{P_0(\lambda_k)}} \approx \sqrt{\frac{5.1 \times 10^8}{3.0 \times 10^4}} \approx 130 \quad (24)$$

times better than the SPIDE system at the dc spatial frequency. Figure 3.3.6(b) shows the Fourier domain signal and noise levels for the conventional imager, when the signal is normalized to unity at the dc spatial frequency. Comparing this plot with Figure 3.3.5(b), notice that the noise floor for the conventional imager is a little more than 2 orders of magnitude lower than that for the SPIDER system, in agreement with the calculation. Also, notice that the conventional imager signal level falls off more rapidly with increasing spatial frequencies than it does for SPIDER. This is due to the MTF $|H_{\text{pan}}(\mathbf{u})|$ of the conventional imager, which is also plotted in Figure 3.3.6(b). So, even though noise floor is much lower, the influence of the MTF term reduces the SNR advantage of the conventional imager at higher spatial frequencies. Comparing Figure 3.3.5(b) and Figure 3.3.6(b) the SPIDER system actually has better SNR above $|\mathbf{u}| \approx 3.3$ cycles/m. Figure 3.3.6(a) shows a Wiener filtered version of the simulated panchromatic image. While there is less overall noise in the conventional image, the SPIDER reconstruction shown in Figure 3.3.5(a) appears to have slightly better resolution. The separation between the solar panel sections and small components on the satellite bus are resolved a bit better in the SPIDER image.

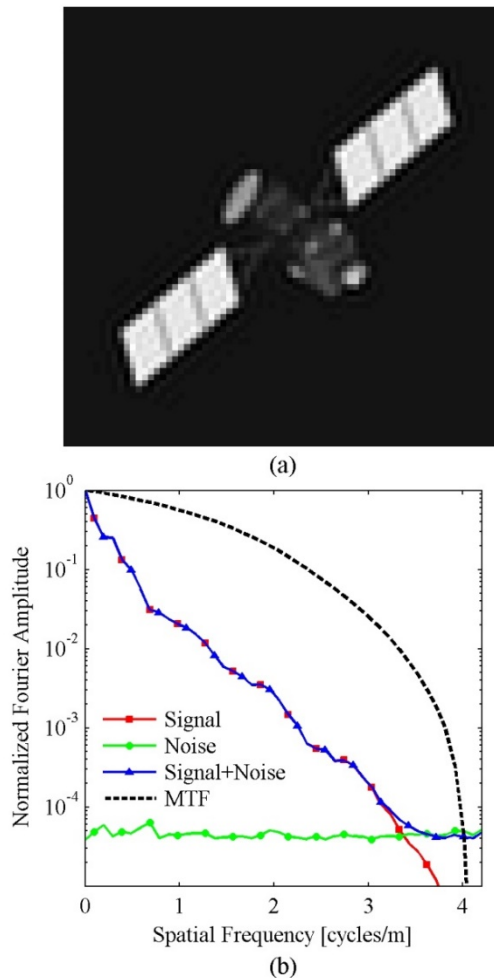


Figure 3.3.6 Conventional panchromatic imaging simulation results: (a) Wiener filtered image; and (b) plot of the normalized signal and noise levels vs. radial spatial frequency. The curves in (b) are normalized such that the signal level equals unity at the dc spat.

4. Publications

1. "Experimental demonstration of interferometric imaging using photonic integrated circuits", Tiehui Su, Ryan P. Scott, Chad Ogden, Samuel T. Thurman, Richard L. Kendrick, Alan Duncan, Runxiang Yu, and S. J. B. Yoo, *Optics Express*, 2017.
2. "Photonic integrated circuit-based imaging system for SPIDER," Katherine Badham, Richard L. Kendrick, Danielle Wuchenich, Chad Ogden, Guy Chriqui, Alan Duncan, Samuel T. Thurman, S. J. B. Yoo, Tiehui Su, Weicheng Lai, Jaeyi Chun, Siwei Li, Guangyao Liu, *OSA Conference on Lasers and Electro Optics Pacific Rim (CLEO-PR)*, August 2017.
3. "SPIDER: Next Generation Chip Scale Imaging Sensor Update", Duncan, A.; Kendrick, R.; Ogden, C.; Wuchenich, D.; Thurman, S.; Su, T.; Lai, W.; Chun, J.; Li, S.; Liu, G.; Yoo, S. J. B., *Proceedings of Advanced Maui Optical and Space Surveillance Technologies Conference*, 2016.
4. "Progress on Developing a Computational Imager Using Integrated Photonics", Samuel Thurman, Alan Duncan, Richard Kendrick, Chad Ogden, Danielle Wuchenich, Tiehui Su, Shibnath Pathak, Wei-Cheng Lai, Mathias Prost, Roberto Proietti, Ryan Scott, S. J. Ben Yoo, *2016 SIAM Conference on Imaging Science*, 2016.
5. "Demonstration of a Photonic Integrated Circuit for Multi-baseline Interferometric Imaging", Ryan P. Scott, Tiehui Su, Chad Ogden, Samuel T. Thurman, Richard L. Kendrick, Alan Duncan, Runxiang Yu, and S. J. B. Yoo, *IEEE Photonics Conference (IPC) (Postdeadline)*, October 2014.