Experimental demonstration of interferometric imaging using photonic integrated circuits

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Abstract: This paper reports design, fabrication, and demonstration of a silica photonic integrated circuit (PIC) capable of conducting interferometric imaging with multiple baselines around \(\lambda = 1550\) nm. The PIC consists of four sets of five waveguides (total of twenty waveguides), each leading to a three-band spectrometer (total of sixty waveguides), after which a tunable Mach-Zehnder interferometer (MZI) constructs interferograms from each pair of the waveguides. A total of thirty sets of interferograms (ten pairs of three spectral bands) is collected by the detector array at the output of the PIC. The optical path difference (OPD) of each interferometer baseline is kept to within 1 \(\mu\)m to maximize the visibility of the interference measurement. We constructed an experiment to utilize the two baselines for complex visibility measurement on a point source and a variable width slit. We used the point source to demonstrate near unity value of the PIC instrumental visibility, and used the variable slit to demonstrate visibility measurement for a simple extended object. The experimental result demonstrates the visibility of baseline 5 and 20 mm for a slit width of 0 to 500 \(\mu\)m in good agreement with theoretical predictions.

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References and links

1. Introduction

The interferometry techniques use superimposed electromagnetic waves to extract information of the wave source [1, 2]. In astronomy, an interferometer uses far-field spatial coherence measurements to extract intensity information from a source to form an image [3]. Examples include the Very Large Telescope Interferometer [4], the Navy Precision Optical Interferometer [5], and the Very Long Baseline Interferometer [6]. 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) [7–9]. 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 [8]. 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 [10] 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 [3].

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.

2. 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 \( I_{\text{tot}} \) also changes.

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

(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 \( \gamma_{12} \) term is the complex degree of coherence, which represents the coherence between the light collected each aperture. In Goodman’s notation [2], \( \gamma_{12} \) 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 \( \pi \) out of phase with respect to this expression.

We can calculate the absolute value of the visibility \( V \) from the above cosine intensity function,

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

(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. \( \gamma_{12} \) is related to the source intensity distribution through a Fourier transform relationship by the van Cittert-Zernike Theorem [2, 11]. The phase of the fringes is related to the phase of \( \gamma_{12} \) 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 [12].

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 lens 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.

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. \( B_{\text{min}} \) and \( B_{\text{max}} \) 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 \( 2 \times 2 \) 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) [12].

![Fig. 2. (a) Layer-by-layer break down of the SPIDER telescope. (b) Working principle of the PIC [7].](image)
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. 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 µm wide and 5.2 µm 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 µm 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 $l_{coh} = \lambda^2 / \Delta\lambda = (1550 \text{ nm})^2 / 20 \text{ nm} = 120 \mu\text{m}$. 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.

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 [13]. 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.

4. PIC Characterization

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.

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 \(\pi\) 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.

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 \(\mu\)m \(\times\) 7.3 \(\mu\)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 µm × 500 µm in size. The measured output waveguide mode size is 61 µm × 7.0 µm.

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.

5. 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 [7].
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 \((D = 3 \text{ mm}, f = 7.5 \text{ mm})\) 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 \(2 \times 2\) 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 \(-5° \text{ C}\). For optimum mode match, we designed the waveguide pitch to be 200 µm and the output mode width in x-axis to \(\sim 70 \mu\text{m}\). With a \(\sim 2.5 \text{ mm}\) 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.

6. 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.

\[
I_{\text{norm}} = \frac{I_{\text{tot}} - I_1 - I_2}{2\sqrt{I_1 I_2}} 
\]  

(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.
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 µm, 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 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.

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

$$\Delta \varphi = \frac{2\pi}{\lambda} \cdot \overline{B \cdot \delta B} = \frac{2\pi}{\lambda} \frac{\Delta x}{F} B$$

Equation (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.
Then we studied the fringe data from a variable width slit [14]. 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.

$$V = \sin\left(\frac{wB}{\lambda F}\right)$$ \hspace{1cm} (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 ~20% lower than ideal, and that of the long baseline is ~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.
7. 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 [15]. Figures 14(b) and 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 $\pi$ 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 $\mu$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.](image)

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 $\mu$m 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 $\mu$m for all four lenslets. This measurement helped us improve the alignment accuracy of individual lenslets.
8. **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 [16] can help significantly eliminate the crossing loss.

9. **Summary**

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.

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