

Multi-Gbps Fiber-Optic Wavefront Sensing Coherent Optical Receiver

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ABSTRACT

We report recent progress on technology developments at the NASA Glenn Research Center using photonic lanterns for coherent optical communications applications. In particular, the development of a spatial mode-diversity optical receiver using a photonic lantern combined with a photonic integrated circuit (PIC). The PIC is designed for compatibility with the NASA Laser Communication Relay Demonstration's (LCRD) differential phase-shift keying signaling format. We report on the PIC design and future characterization and packaging efforts. Additionally, we report on the development of a 19-channel photonic lantern and provide updates on efforts to use the photonic lantern as a wavefront sensing device. The photonic lantern insertion loss, and spatial-mode transfer characteristics are detailed, as well as the development of a predictive framework in which the intensities in the 19 single-mode output channels are used to reconstruct the wavefront of the light entering the multi-moded input side of the lantern. Finally, we discuss concepts for potential future systems using photonic lanterns and PICs that combine both wavefront sensing and coherent communications onto a single integrated platform.

Keywords: Optical communications, photonic lantern, spatial-mode diversity, wavefront sensing, photonic integrated circuits

1. INTRODUCTION

NASA communications and navigation systems in the Lunar environment envisioned for the 2030's and beyond will need to accommodate human exploration, science experiments, human and robotic mobility operations, basecamp operations, and other missions in general requiring high data-volume transmissions. Thus, future systems will need to overcome the current limitations of present-day communications systems. It has been well-recognized that optical communications systems offer a number of advantages compared to radio-frequency (RF) systems, particularly lower size, weight, and power (SWaP), as well as a virtually unlimited available bandwidth that enables far higher data rates, reduced contact time and ultimately larger data return. Additional advantages are orders of magnitude link efficiency and security due to comparatively narrow beam divergence. For these reasons, optical communications, particularly coherent optical modulations, are being considered by NASA to provide Lunar surface links and high-rate direct-to-Earth (DTE) links.

However, the coherent optical communications systems envisioned for multi-Gbps Lunar DTE links require bulky and costly adaptive optics on the ground station, in order to preserve the phase encoding of the received signal after distortion through the atmosphere. As an alternative, it has been shown that through use of a multi-aperture receiver array and digital coherent combining, unwanted effects of atmospheric turbulence can be significantly reduced through spatial mode diversity.¹ A further simplified alternative, proposed here, in place of a multi-aperture telescope array, a fiber optic photonic lantern can be used with a single telescope (Figure 1). In such a device, a multi-mode fiber input is adiabatically split into multiple single-mode, or fewer-mode, outputs, in which the single-mode output end comprises an array of isolated uncoupled single-mode waveguides. In this way, the photonic lantern can provide similar spatial diversity as a multi-aperture array, but with considerable

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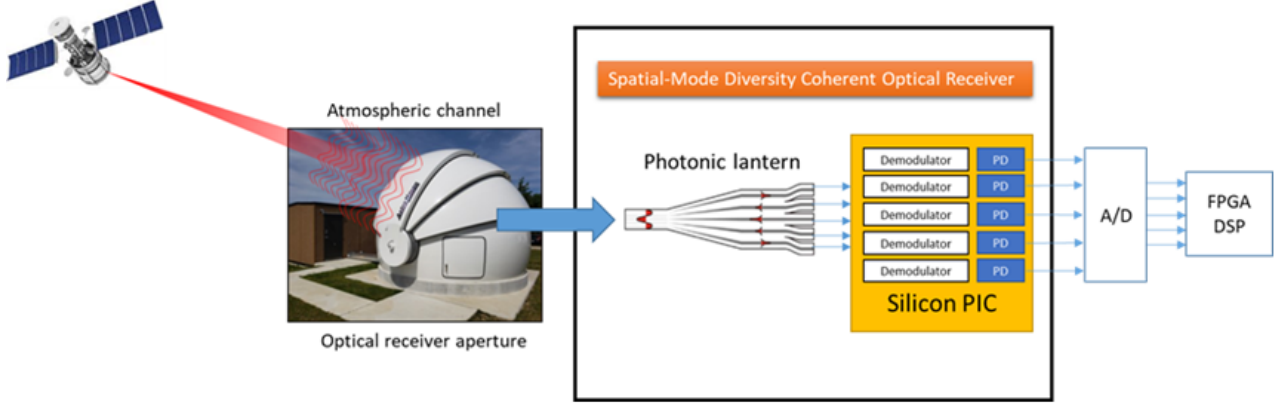


Figure 1: Spatial-mode diversity coherent optical receiver system.

savings in SWaP, complexity, and cost, since only a single telescope is required, and the photonic lantern itself is a simple passive fiber optic.

Further savings in SWaP, complexity, and cost can be realized on the optical demodulation and detection front end. In a high-rate coherent optical communications system that utilizes modulations such as differential phase-shift keying (DPSK), as does NASA’s Laser Communications Relay Demonstration (LCRD),² a delay line interferometer (DLI) and two balanced photodetectors with amplifiers are required in the receiver. As a solution, we propose a silicon photonic integrated circuit (PIC), with size much less than 1 cm^2 , that can couple to the photonic lantern and incorporate on-chip DLIs and photodetectors, serving as the optical front-end demodulating and outputting electrical signals for further processing. Due to the size of the chip and device density in silicon, the PIC could accommodate many 10s of channels, in addition to a wide variety of other functions such as narrowband filtering, and wavelength multiplexing.

2. DPSK RECEIVER PHOTONIC INTEGRATED CIRCUIT

The PIC was designed to support differential phase-shift keying (DPSK) demodulation and fabricated through the AIM Photonics multi-project wafer (MPW) platform. Due to optical I/O constraints we were limited in this case to 4 channels per chip. DSPK demodulation can be implemented as an unbalanced Mach-Zehnder interferometer (MZI) with the long arm optical path length delayed by a single bit period (Figure 2a). The MZI outputs are then read-out through a balanced photodiode configuration. Other implementations of DPSK demodulation have been demonstrated in silicon photonics, particularly designs based on microring resonators.^{3–7} For 2.88 Gbps DPSK the delay line corresponds to a free-spectral range (FSR) in the interferometer transmission vs. wavelength transfer characteristic of $FSR \approx 23.08 \text{ pm}$ (Figure 2b). Thus the required 1-bit MZI delay line length is $\approx 2.6 \text{ cm}$ for a silicon strip waveguide with group index $n_g \approx 4$. However, the required length can result in a lossy implementation since a typical 220-nm, 500-nm wide silicon-on-insulator (SOI) strip waveguide can have propagation losses on the order of a few dB/cm. For the required path length this could result in an unacceptable signal loss of greater than 7 dB per channel, not including fiber coupling or other losses.

To reduce the waveguide loss in the long arms of the MZIs while achieving the required optical path length, we divide the long arms into 24 sections of $2\text{-}\mu\text{m}$ widened waveguides, 1.2 mm in length, for a total area of $\approx 0.12 \text{ mm}^2$ per channel. The wider waveguides reduce the effects of sidewall scattering when the fundamental propagating TE_{01} mode is primarily confined to the center of the waveguide, and away from the sides. To ensure single-mode propagation in an otherwise multi-moded waveguide without exciting higher-order modes, we adiabatically taper the waveguide from 500 nm up to $2 \mu\text{m}$ (Figure 3, left side). The taper profile was derived using the Fourier modal method,⁸ and designed to minimize perturbations. Each $2\text{-}\mu\text{m}$ waveguide section is then serially connected by an Euler U -bend, also shown in Figure 3 (right side). The U -bend is comprised of a mirrored section of an Euler spiral, which features a continuously varying radius of curvature. This geometry

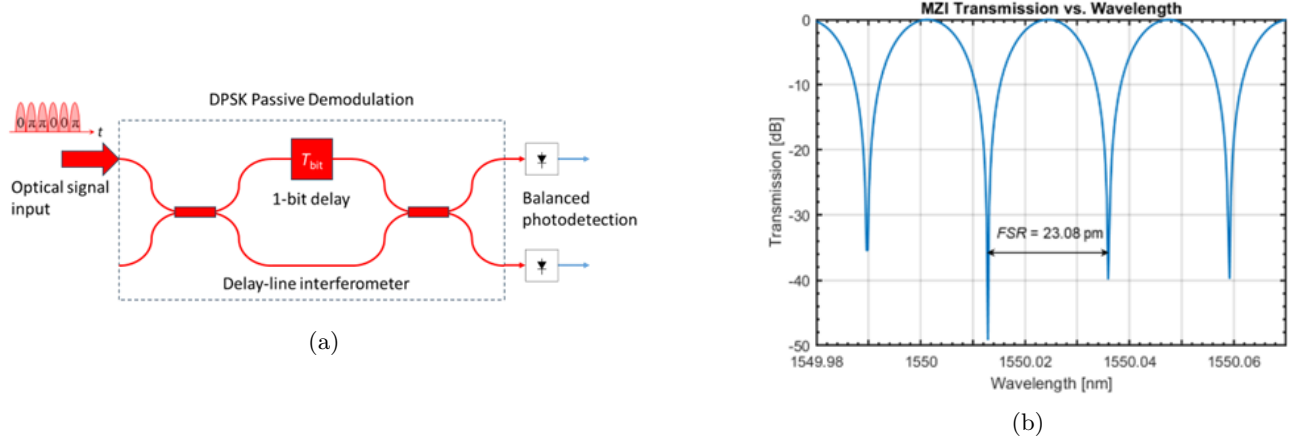


Figure 2: (a) Diagram of a passive DPSK demodulator implemented as a delay line interferometer (DLI). (b) Plot of a simulated waveguide interferometer transmission vs. wavelength.

allows the fundamental propagating mode to couple into higher-order modes throughout the bend, and then back into single-mode with minimal radiation-mode coupling, and hence minimal loss.⁹ This allows for a tighter bend than is achievable with a fixed radius, and thus a more compact footprint. A similar implementations of this design has demonstrated losses $\ll 0.1$ dB for the *U*-bend and taper, as well as < 0.1 dB/cm for the multi-mode waveguide sections,¹⁰ indicating that the total loss of the delay arms will be on the order of 2.5 dB or less.

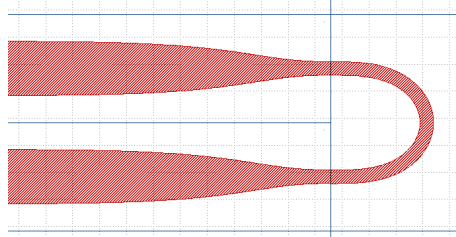


Figure 3: Adiabatic waveguide transition and *U*-bend connection between waveguides.

The fabricated 4-channel DPSK passive demodulators are shown in Figure 4a. Light is coupled in to the chip through fiber edge couplers on the bottom right of 4a, and each interferometer arm outputs to a pair of differentially-wired photodiodes (not shown). The photodiodes will be wirebonded to a printed circuit board with electrical bias and read-out transimpedance amplifier (TIA) circuits for final packaging and testing.

3. PHOTONIC LANTERN WAVEFRONT SENSOR

While the photonic lantern/photonic integrated circuit (PL-PIC) receiver concept is mainly focused on the application of a photonic lantern as a low-loss interconnect between the telescope and PIC demodulator, there are other possible applications as well. It has been shown that a photonic lantern has a well-defined input/output spatial mode transfer matrix, such that the input wavefront can in principal be reconstructed from measured output intensities on each channel.¹¹ This gives a possibility of a receiver system that could be designed to simultaneously measure wavefront as well as process signals, both which can be implemented as a PIC. For example, in such a system the PL-PIC could be used in combination with a deformable mirror (DM) to manipulate the input wavefront such that the output of the photonic lantern is preferentially into a single fiber, which is then selected for signal demodulation and processing, thereby relaxing the need to process multiple parallel channels. To investigate this application we fabricated a 19-mode photonic lantern and initiated development of a wavefront reconstruction concept.

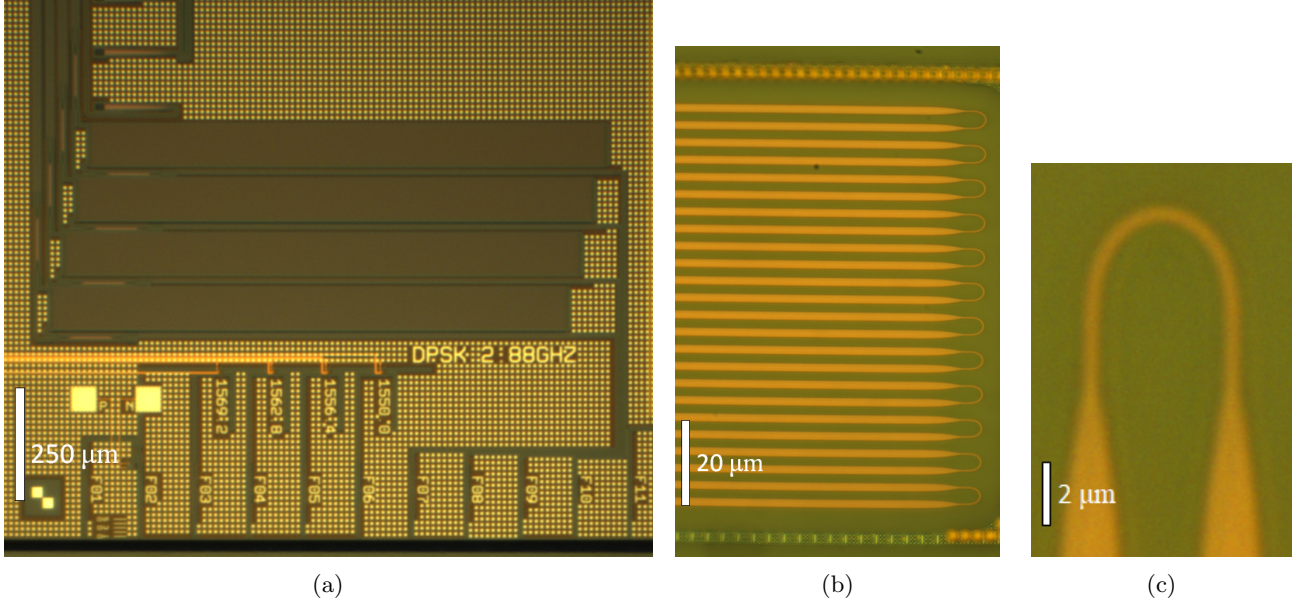


Figure 4: (a) Optical microscope picture of fabricated PIC with 4-channel DPSK delay line interferometers (DLI). (b) Close up of multi-mode waveguide meander for low-loss path length on the long arm of the DLI. (c) Zoomed view of a single U -bend and taper section.

3.1 Photonic Lantern

The photonic lantern was fabricated with 19 single mode fibers for 1550 nm with a core of $\approx 9 \mu\text{m}$. As seen in Figure 5a the photonic lantern has a $54.2 \mu\text{m}$ fused core diameter, with index of refraction of 1.444 at 1550 nm on its multimode input allowing support of 19 spatial modes. The outer diameter of the cladding is $126.4 \mu\text{m}$ with index of refraction of 1.4412 at 1550 nm. The length of the down taper is 30 mm. When coupled with a Gaussian beam the lantern has a 1.4 dB total insertion loss. The photonic lantern is packaged with metal tubes and jacketing to prevent damage (Figure 5b).

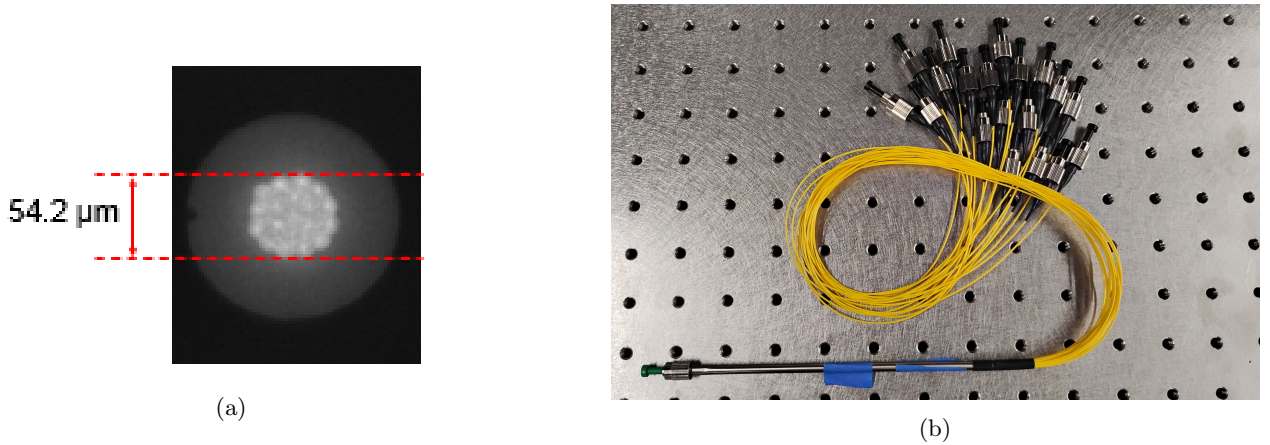


Figure 5: (a) Multi-mode fused core end. (b) Fully packaged 19-channel photonic lantern.

3.2 Wavefront Reconstruction

The mode transfer matrix consists of complex coupling coefficients characterizing the linear relationship between the guided spatial and polarization modes at the input and output of the photonic lantern at a given wavelength.

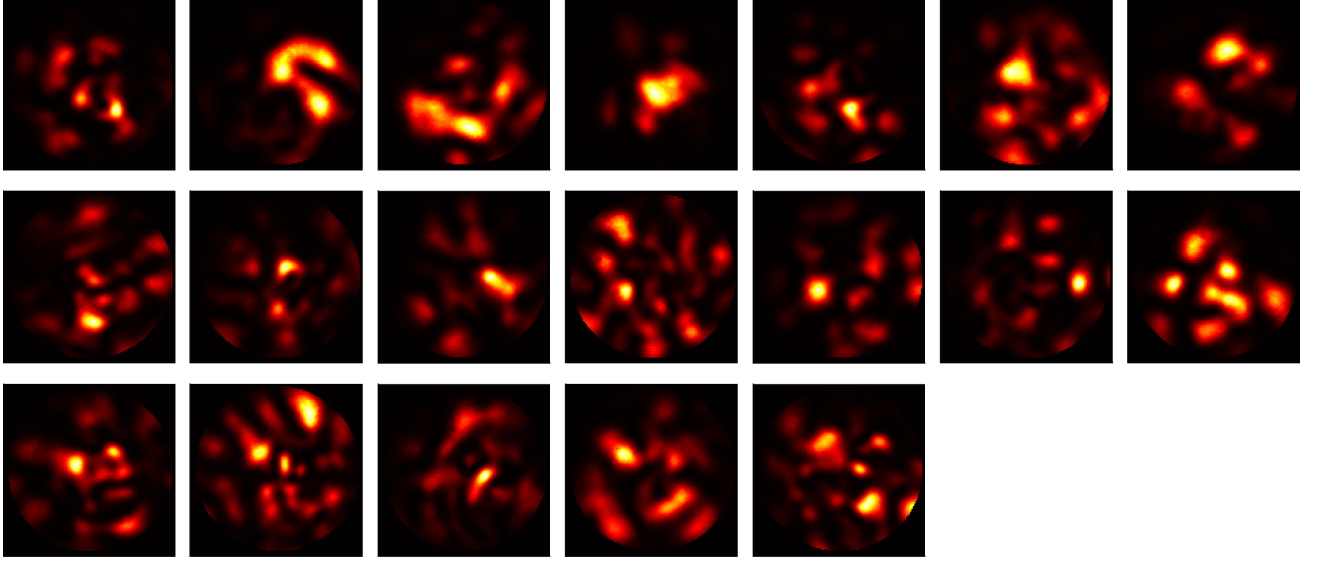


Figure 6: Intensity profiles for all 19 spatial modes emerging from the fused core of the photonic lantern obtained by injecting light into each single-mode fiber leg.

For a lossless optical system, measurement of the amplitude and phase of the light in each output mode together with the mode transfer matrix completely describes the light at the input of the system and hence can be used to reconstruct the wavefront at the input. The photonic lantern naturally provides low-loss spatial mode demultiplexing into isolated output modes in each single-mode fiber leg, enabling wavefront reconstruction limited only by insertion loss at the input of the fiber (dependent on the severity of the wavefront degradation and the number of modes supported by the photonic lantern) together with mode-dependent loss associated to the adiabatic transition in the taper region. In the case that only the output intensities in each leg are recorded (without relative phase), the mode transfer matrix can be augmented with other techniques such as machine learning to attempt an accurate wavefront reconstruction based on partial knowledge of the output state.¹²

In contrast to measurements of the mode transfer matrix of a multi-mode fiber (MMF),^{13,14} in which the guided modes take the form of LP modes with well-understood degenerate mode groups, the guided modes at the input and output of the photonic lantern are not symmetric, and the guided modes at the fused core input and their degeneracies may not be known in advance. In this preliminary work, we report on measurements of the modes obtained by injecting light into each output leg using a high-resolution wavefront sensor based on quadri-wave lateral shearing interferometry (QWLSI) placed after a collimating lens at the fused end of the photonic lantern. Although mode-dependent losses degrade the orthogonality of these modes as a basis for representing the mode transfer matrix, they nevertheless provide information necessary to construct such a basis, either via an orthogonalization procedure, approximation with an appropriate set of LP modes, or eigenfunction decomposition of the Wigner phase space distribution of the weighted sum. Once a complete set of $N = 19$ basis modes is determined, the mode transfer matrix can be obtained from $4N - 3$ measurements per polarization using 19 phase masks applied with appropriately chosen phase offsets.¹⁵

Figure 6 shows intensity profiles of light emerging from the fused core, measured after a collimating lens, corresponding to light injected into each of the 19 legs. Inspection of the intensity distributions and phase gradients showed that each spatial mode was independent of the polarization state injected into the single-mode fiber legs. The complete spatial mode including phase profile reconstructed by the wavefront sensor was tested by injecting the reconstructed spatial mode back through the collimating (focusing) lens into the fused end of the photonic lantern using a spatial light modulator (SLM). Figure 7 shows a measurement of the reconstructed mode shaped by the SLM. Due to large intensity nulls in the mode shapes, it was found that the least-squares phase reconstruction from the phase gradients was insufficient to completely reconstruct the spatial mode, which generally requires also a reconstruction of the ‘hidden phase’ associated to branch point singularities.¹⁶ Several

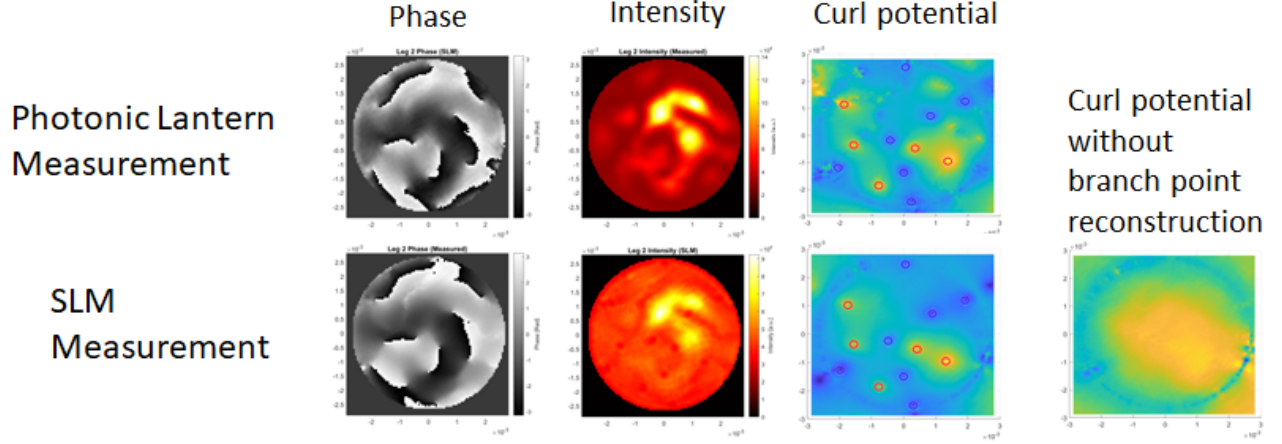


Figure 7: Mode reconstruction based on WFS measurements including branch point identification algorithm. Top row shows the intensity and phase reconstruction including branch points identified from the rotational component of the phase gradients. Bottom row shows a measurement of the reconstructed mode shaped by the SLM and injected back into the fused end of the lantern for verification.

branch point identification algorithms were found to be insufficient for this purpose due to the large low-intensity regions of each mode.^{16,17} Unambiguous reconstruction of the phase profiles obtained by combining the intensity distributions with direct interferometric phase measurements against a collimated reference beam is left for future work.

4. SUMMARY AND FUTURE WORK

We are developing a low-cost, simplified, and highly scalable receiver concept for high-data rate coherent optical communications and atmospheric compensation. To this end we have designed a PIC for 2.88 Gbps DPSK and fabricated through the AIM Photonics MPW, as well as fabricated a 19-channel photonic lantern. We measured the photonic lantern’s mode transfer characteristic and performed initial development of wavefront reconstruction algorithms. Near-term future work will be the completion of the PIC bias and read-out electronics and fiber array integration, and testing with a 7-channel photonic lantern in an end-to-end link. Additionally we will continue to improve the fidelity of wavefront reconstruction from photonic lantern measurements. Longer-term future work will seek to develop multi-channel PIC designs that can accommodate various phase and/or intensity modulations-DPSK, DQPSK, BPSK, QPSK, OOK, PPM, etc., as well as data rates in the 10s of Gbps, begin integration with signal processing electronics, and optical ground station integration and testing.

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