Single photon imaging in the shortwave infrared

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Introduction

- Single photon and low-light imaging has become important in many imaging applications such as LIDAR for autonomous vehicles and medical and biological imaging
- This has been enabled by modern camera technology; state of the art sensors designed to work in the visible region of the spectrum now have noise levels equivalent to 1 photon per pixel.
- However, this is not the case for imaging regimes outside the visible region, for example in the shortwave infrared camera noises can be up to two orders of magnitude higher.
- **We present a coherent detection setup which can eliminate detector noise, and consequently is able to image a signal 200 times lower than the camera noise floor, enabling infrared imaging at the single photon level**[1]

Methods

- Our method relies on the coherent detection of light, where we record not the signal itself but the interference of the signal with a reference beam termed a local oscillator as shown in Fig. 1
- In an effect first described by Gabor[2] in his 'paradox of observation without illumination', it is possible to amplify the signal when the local oscillator is much higher powered when using coherent detection
- Coherent detection in imaging is usually referred to as holography. We record a hologram on the camera with intensity profile:

$$I = I_{ref} + I_{sig} + 2(I_{ref} I_{sig})^{1/2} cos(\varphi)$$

where φ is the relative phase between the two arms

- The key to the performance of the system is the interference term $2(I_{ref} I_{sig})^{1/2} cos(\varphi)$, which is used to reconstruct the image of the object. Even if the intensity of the signal is low, the interference term can be amplified by increasing the intensity of the reference beam
- We recover intensity and phase images from the object hologram with standard digital holography techniques[3]

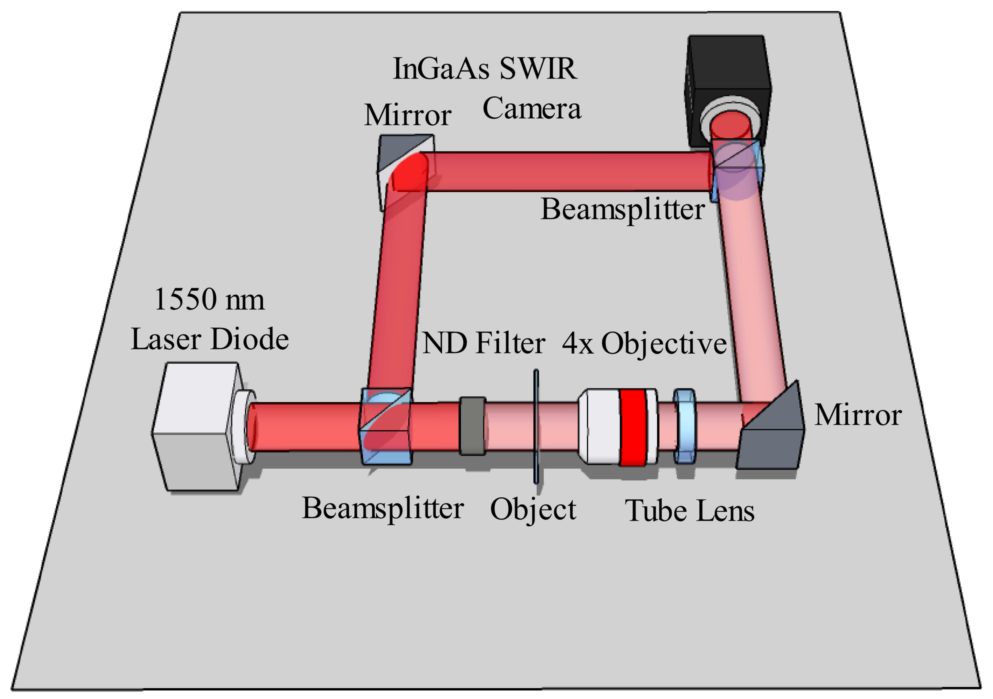

Fig. 1. Diagram of the experimental setup used to obtain low light holograms of the image

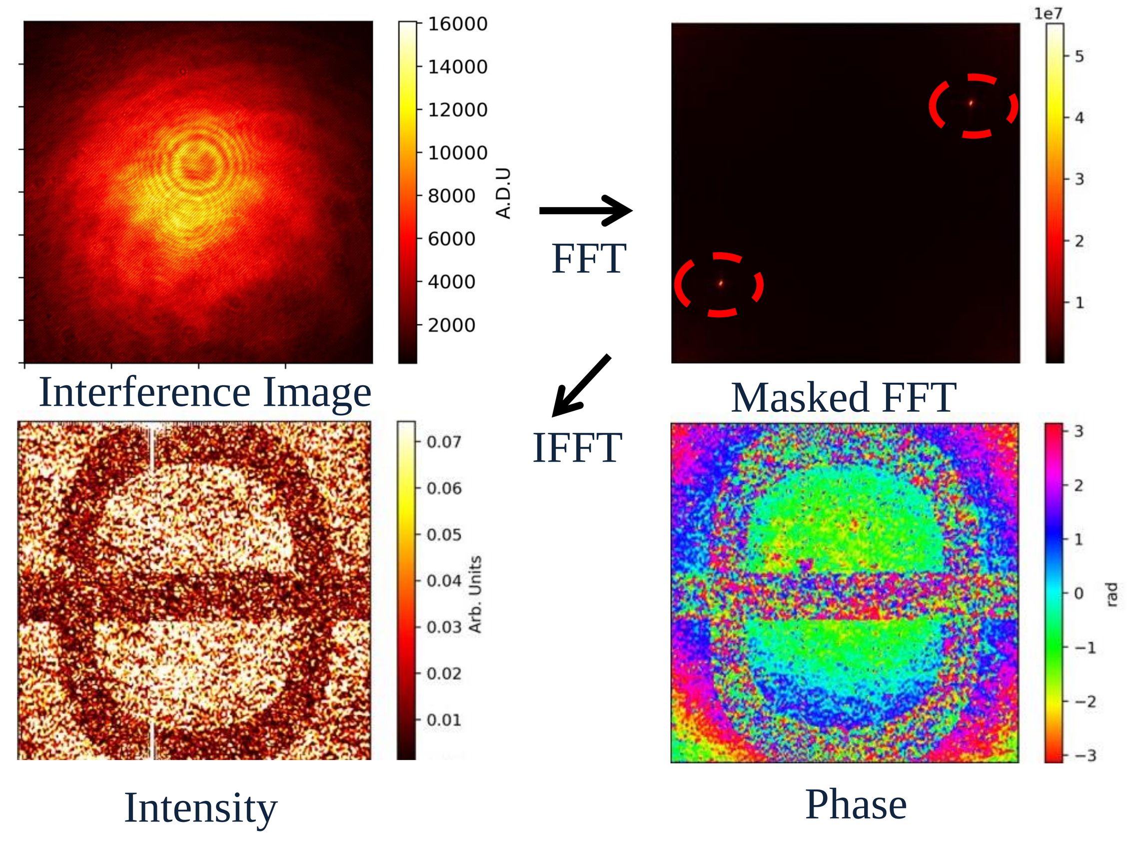

Fig. 2. Schematic of the image reconstruction process. Red dotted circles on the FFT image indicate the regions around which a filter is applied to select the spatial frequencies corresponding to the image of the object

Results

- Fig 3 shows a series of images taken at different probe and reference intensities, down to a detected probe signal of ~1 photon per pixel per frame
- With the readout noise of the sensor used being ~180e⁻ per pixel (~212 photons per pixel at 85% QE) this represents a large increase in the sensitivity of detection

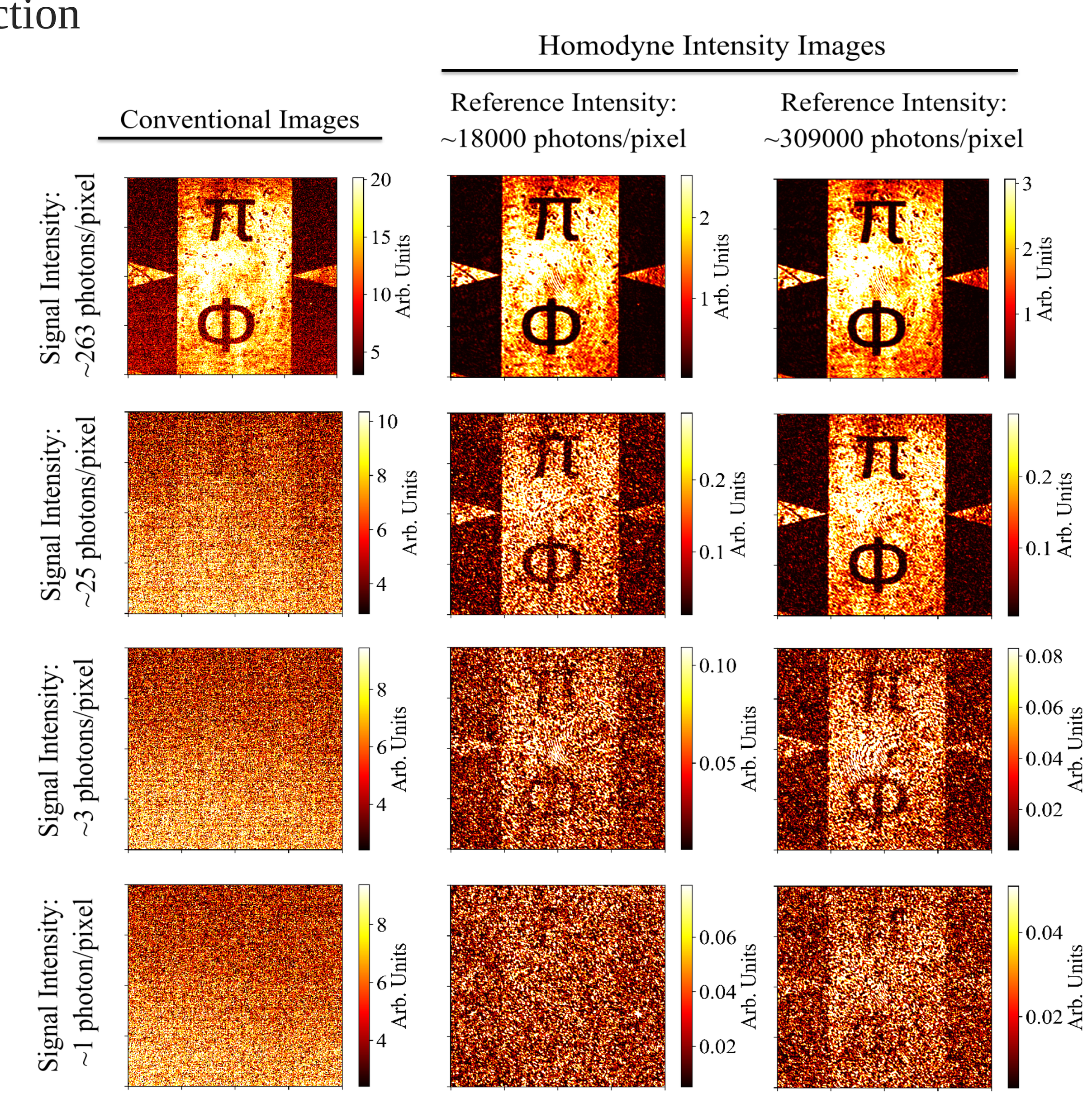

Fig. 3. Single frame acquisitions of a silicon chip under a range of illumination scenarios. Shown are conventional images along with their corresponding holographic intensity images at two different reference intensities. The increased noise at a lower reference intensity demonstrates the effect of the reference amplifying the signal

Phase Imaging

- Holographic imaging systems also allow for access to phase as well as intensity images, which show information about the optical path of the signal beam
- We demonstrate that our system is capable of obtaining intensity and phase images of an object with a complex transmission profile, even when the illumination level is below the noise floor of the camera as seen in Fig. 4

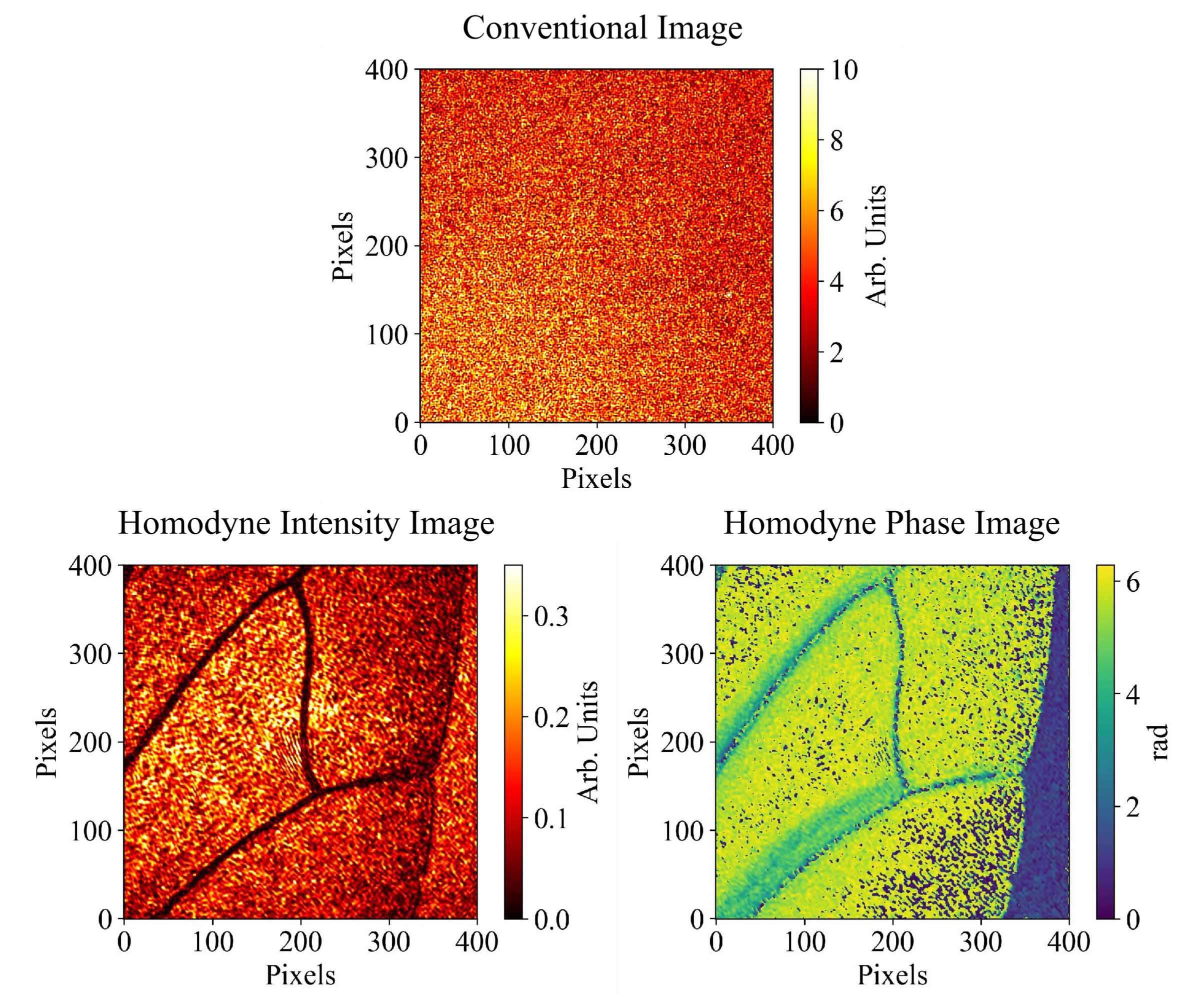

Fig. 4. A conventional image of a fly wing along with the corresponding intensity and phase images taken with the homodyne system, showing the ability of the system to image an object with a complex transmission profile. Images taken at a signal intensity ~25 photons per pixel per frame

Discussion

- We have demonstrated an imaging system capable of imaging at the single photon level, despite the camera having a noise floor ~200 times higher
- Our system is capable of working in real time and on a single camera frame using off-axis holography for image reconstruction
- We believe our demonstration will extend the applications of single photon imaging systems beyond the visible region of the spectrum, as well as other challenging detection regimes such as imaging at kHz frame rates

References

[1] O. Wolley et al., Near single photon imaging in the shortwave infrared. (2023)
[2] D. Gabor, Light and information. (1961)
[3] K. Fatemi & G. Beadie, Rapid complex mode decomposition of vector beams by common path interferometry. (2013)