A high-resolution single-photon camera based on superconducting single photon detector arrays and compressive sensing*

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We present our results on utilizing a superconducting nanowire single photon detector array and compressive imaging techniques to perform single photon imaging and present our results on a high-resolution single-photon camera.

Introduction

Imaging using single photons in the near- and mid-IR regime will have an impact on applications such as remote sensing, greenhouse gas imaging and surveillance. Recently, superconducting nanowire single photon detectors (SNSPDs) have shown high detection efficiencies in the near-IR [1] and have the potential to achieve high efficiency single photon detection for wavelengths in the mid-IR. Also, because of their good timing resolution, the single photon time-of-flight information can be utilized in ranging applications [2]. However, imaging applications require large numerical aperture detectors, and standard fiber-coupled SNSPDs do not offer such capability. We recently developed a free-space coupled SNSPD array [3], which can be used as a large numerical aperture detector. We utilize this SNSPD array and compressive imaging techniques and present to establish a high-resolution single-photon camera.

Theory

Compressive imaging utilizes the sparsity of a scene by finding the major components of a small basis set representing the scene [4-6]. Generally, a single pixel detector is used for detection, and a digital micro mirror device (DMD) chooses a series of quasi-random orthogonal sampling matrices with known basis to extract information from the scene. We can represent the image as a single vector (x) of length N^2, where N^2 is the resolution of the DMD, *e.g.* 256x256 pixels ($N = 256$):

$$y = \Phi x \tag{1}$$

Φ represents an N^2xM matrix of sampling vectors ϕ each with length N^2. M is the number of sampling vectors used for the image acquisition. ϕ represents an NxN pattern that will be uploaded onto the DMD and intercept the image's information (intensity) content. The measurement outcome y represents the projection of the image vector onto the sampling vector. A single sampling vector is a quasi-random arrangement of +1 and -1, based on a Hadamard matrix of size N^2x N^2. The rows of this Hadamard matrix represent an orthogonal basis set, *i.e.* there is a unique measurement outcome for each of the sampling vectors. Since a raw Hadamard matrix has repeating patterns within its rows and columns, one has to randomly permute all columns of this matrix and subsequently randomly choose M rows as the sampling vectors ϕ. Only then, the sampling vector represents a quasi-random distribution of +1 and -1. In order to translate the ±1 Hadamard representation to the on/off (1/0) setting choices of the DMD, we split the measurement into two separate DMD sampling vectors. The first vector is realized by setting all elements of the Hadamard sampling vector that are equal to '1' ('-1') to a DMD setting 'on' ('off'). The second vector is the inverse of the first one, *i.e.* 'on' → 'off' and 'off' → 'on'. Performing both measurements in sequence and subsequent subtraction of the measurement outcomes y results in background-subtracted measurement outcome equivalent to probing the image with a Hadamard representation. The advantage of using compressive sensing for image reconstruction is the fact that a scene (image) is generally sparse. Instead of rasterscanning the scene and requiring N^2 measurements, one can acquire the image with usually less than $0.1 \cdot N^2$ measurements ($M \approx 0.1 \cdot N^2$). After performing an image acquisition, we analyzed the measured intensities using the TVAL3 algorithm [7].

Experiment

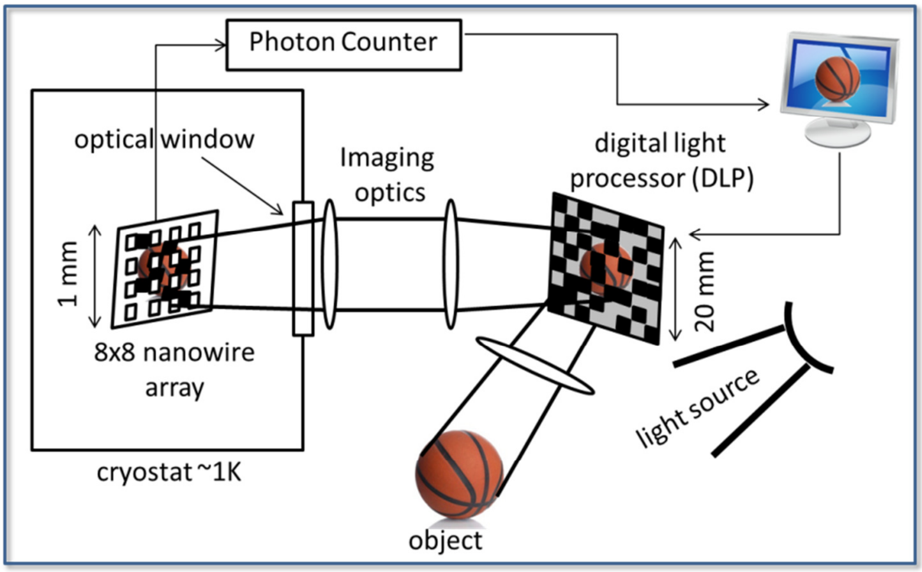

Figure 1. Experimental Setup. An object is projected onto a digital micro mirror device (DMD). The projected image is projected onto an 8x8 SNSPD array for single photon counting.

Figure 1 shows our experimental setup. A light source illuminates an object which is projected onto a DMD. The DMD is probing the object with matrices obtained from randomly chosen rows of the randomly permuted columns of a Hadamard matrix. This way a quasi-random orthogonal set of sampling matrices is used to probe the object. By use of another set of imaging optics the reflected pattern is projected onto an 8x8 SNSPD array inside an optical cryostat, cooled to ≈1 K. SNSPDs [8] are based on thin and narrow superconducting wires, typically 150 nm wide and 5 nm thick. A current close to the critical current of the nanowire is passed through the nanowire. A photon absorbed by the nanowire causes localized heating and the nanowire becomes resistive. This 'hotspot' forces the superconducting current to divert around its resistive region. This diversion of the superconducting current, in turn, will cause the current to exceed the critical current density of the nanowire and the nanowire will become normal, leading to an electrical pulse travelling along the wire which can be amplified and measured with room-temperature electronics. We use WSi as the superconducting material. Recently, high detection efficiencies in the telecom regime [1] and mid-IR responses [9] were demonstrated using WSi. Also, the intrinsic dark count rate of these detectors was shown to be exceptionally small [1]. The size of the SNSPD array is ≈1 mm x 1 mm. Each SNSPD is a 30 µm-square and the pitch is 150 µm. The pitch of 150 µm was chosen to allow for fill-factor enhancement using a commercially available microlens array (MLA). The size of the SNSPD array also allows large numerical aperture imaging. We integrate the total single photon flux among all 64 pixels of the SNSPD array to receive the total intensity of the pattern reflected off the DMD (y). Since the light is free-space coupled onto the SNSPD array, a series of optical filters inside the cryostat was used to eliminate the black body radiation originating from the room temperature environment. For the results presented here, we chose a filter passband of 650 nm ± 20 nm. This wavelength selection is in the visible wavelength regime and shows the proof-of-concept of our proposed method.

Results and Discussion

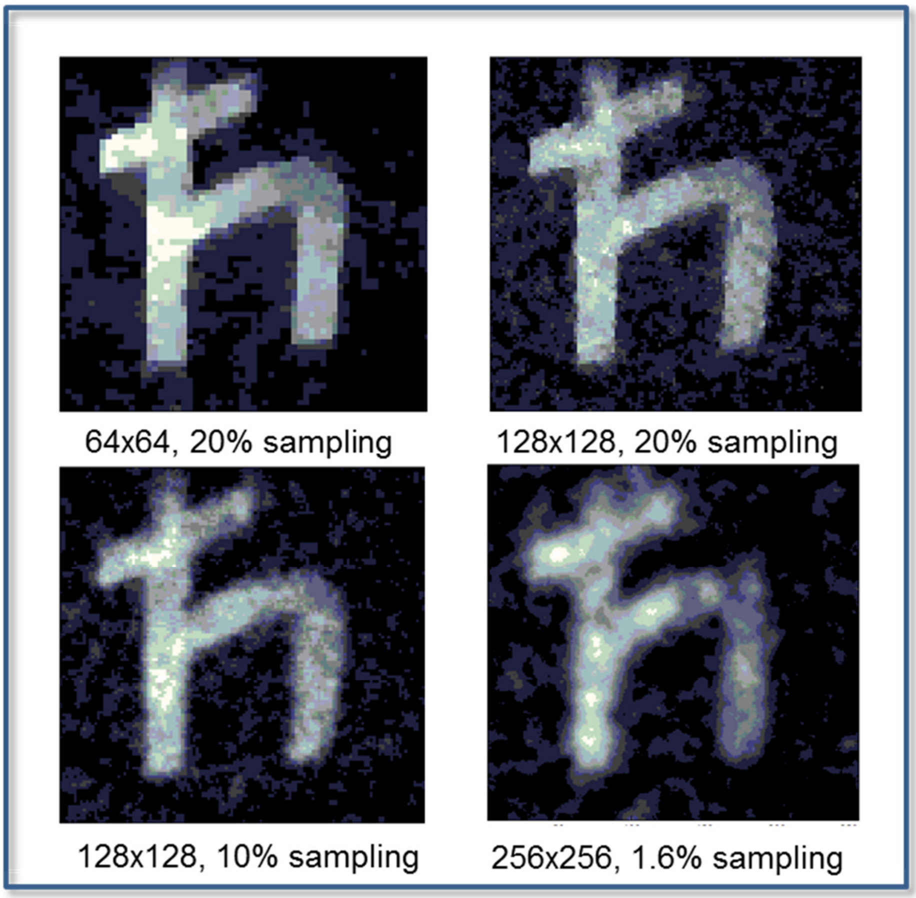

Fig. 2. Experimental Results: Object illuminated with a white light source and different resolutions on the DMD. Left to right: DMD resolution/sampling ratio: 64x64/20 %, 128x128/20 %, 128x128/10 %, 256x256/1.6 %; Total samples taken: 820, 3280, 1640, 1050

Figure 2 shows our results. We used the TVAL3 solver [7] for reconstructing the object from our compressive imaging data. We sampled the object with various resolutions on our DMD. The sampling ratio depended on the resolution of the image. For the 64x64 pixel image, a 20 % sampling ratio corresponding to 820 sampling matrices and 1640 measurements were used. An acquisition at a resolution of 128x128 pixels was done for two sampling ratios of 10 % and 20 %. The quality of the image only slightly improves when sampling with a ratio of 20 % compared to 10 %, indicating that the object is highly compressible in the sparse basis. The highest resolution of 256x256 pixels only required a sampling ratio of 1.6% to achieve reconstruction of the object with good signal-to-noise.

The above results indicate that the free-space coupled SNSPD arrays can in fact be utilized for the purpose of compressive imaging. Since the SNSPDs are sensitive in the mid-IR regime, we expect to be able to perform single photon imaging in the mid-IR regime in the near future. Along with the good timing resolution of the SNSPDs, we will also be able to provide a depth map [10] of the acquired image at the same time.

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