Quantum correlations for hiding images in noise

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ABSTRACT

A limitation of free-space optical communications is the ease with which the information can be intercepted. Overcoming this limitation is possible by hiding the information within the background optical noise that is present in all real-world situations. We demonstrate the limitations of our experimental system for transferring images over free-space using a photon-pair source emitting two correlated beams. The system uses spontaneous parametric down-conversion to create photon-pairs, where one photon contains the spatial information and the other the heralding information.

Keywords: Quantum imaging, Correlated photon source, Single photon imaging, Steganography

1. INTRODUCTION

The ability to transmit hidden images has often been performed digitally, where steganography can be used to conceal an image within another image via encoding.[1,2] A physical method of hiding images has been demonstrated with spatial quantum correlations, where an image formed of spatial correlations could be mixed with thermal light. The image formed of the spatially correlated photons can be separated from the thermal light using the knowledge given by the correlated light.[3–6] This work also relates to quantum LIDAR (light detection and ranging), where using correlated-photon sources that have a low intensity in comparison to the background light levels means the probe light cannot be detected by other observers. Due to the low photon number a compliant target is often used, where the target will give a high return of correlated photons to the detecting optics.[7] This technique has been shown to be highly tolerant to jamming attacks, where an external party tries to flood the LIDAR with light to reduce the ability for the transmitted to detect the reflected light.[8] The general requirement for an image constructed from individual photons is that the signal be above the shot noise of a given pixel for the photons not within the image. This gives a condition where there is fundamental limitation on our heralding image for what measurement can be performed in the presence of shot noise without using more complex techniques.[9,10]

In our previous work we demonstrated how images could be transmitted by hiding the images within noise, where an observer without knowledge of heralding information is unable to reconstruct the image.[11] In this paper we present characterisation of the image transmission system in sending an image, we quantify the capability for the system to reject a background photons and understand the limitation of the heralding system to deal with external background light. Via direct measurement the limitation of the observing system using the heralding system is presented and thereby showing that the image can be reconstructed with a very high rejection of background noise.

2. METHODOLOGY

The light used was a temporally correlated photon source as described in Ref. 7. Via the process of spontaneous parametric down conversion (SPDC) two photons are produces that are correlated in time. The experimental system that has demonstrated heralding imaging with a correlated photon source, and used within this paper,

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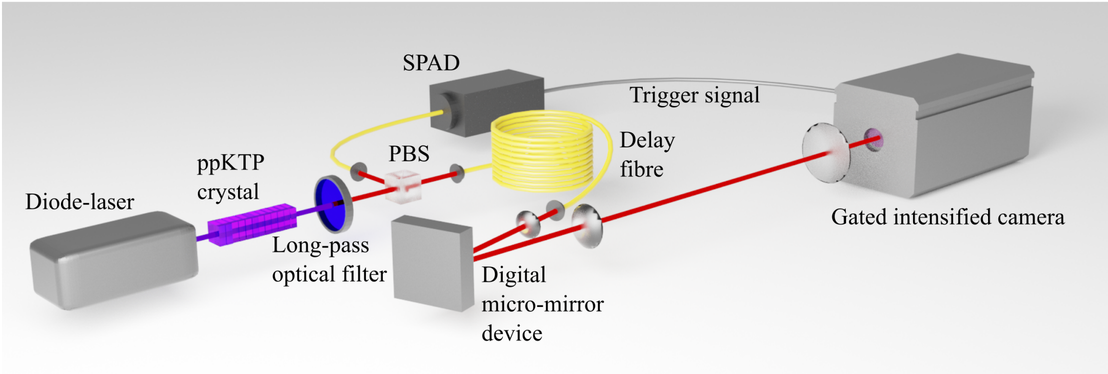

Figure 1. The diode laser and ppKTP crystal form the correlated photon source, which produces pairs of temporally correlated photons are separated by a polarising beam splitter (PBS). One of the photons enters a short optical fiber to trigger a single-photon avalanche diode (SPAD) that triggers the gated intensified camera. The other photon enters a delay line and is then incident on a DMD displaying an image that is imaged on to the camera, the digital delay within the camera is set such that the temporally correlated photon is captured during the activation of the gated intensified camera. The figure is reproduced with permission from Ref. 11.

has been fully described in Ref. 11. The photon-pairs from the SPDC have orthogonal polarisation and are split using a polarising beam splitter, where one photon is sent to a single photon avalanche detector (SPAD) and the other is sent to a projection system. The projection system is similar to a conventional data-projector, where a digital micro-mirror device (DMD) comprising of many small mirrors that can be programmed to reflect the desired part of the light source to be projected via a lens to form an image. In the experiment the camera used to act as the observer was a gated intensified camera, this CCD camera had an intensifier to increase the signal from individual photons reaching the camera. When the SPAD received one of the correlated photons it would trigger the camera to activate the image intensifier and the other temporally correlated photon of the pair would be recorded by the camera. The camera received the trigger signal the intensifier would fire for a 10 ns gate time to measure light that reached the camera during that period, all other light outside of the gating window would not be recorded by the sensor. To ensure the correlated photon was recorded the camera has a digital delay, such that the time between the trigger signal and the gate being fired could be adjusted, by measuring a series of delay times the optimum delay was set such that the temporally correlated photon would be measured with the gated window.

During the alignment of the paired-photon source two SPAD detectors were used, one on each output of the polarising beam splitter. The source was set up to produce 130 000 photon-pairs per second, as measured by a two SPAD detectors during the alignment of the source (SPAD quantum efficiency $\approx 50\%$). The signal measured within the temporal correlation window was compared to the total counts recorded by the detectors, the system was optimised such that 9.6% of the photons detected were within the correlation period, the system measured $\approx$13 000 photons-per-second in the correlation time period, where the remaining photons are uncorrelated.

To measure how insensitive the heralding system was, it was operated in two modes: running the camera without triggering input from the correlated photons and using the heralding information to trigger the gated intensifier. Having an external light source, the light level was increased until it was no longer possible to see the heralded image.

3. RESULTS

The projection system was set up to project the number "2" to be imaged onto the gated intensified camera. Images were taken with an exposure time of 1 second, to compile an image of 100 individual exposures that were summed together. The region of interest on the camera was 180×180 pixels (camera pixel size of 13 µm), which covered the projection area for the correlated photon beam. Analysing each 1 second image, the number of photons arriving from the photon source was calculated by counting the individual photons. The number

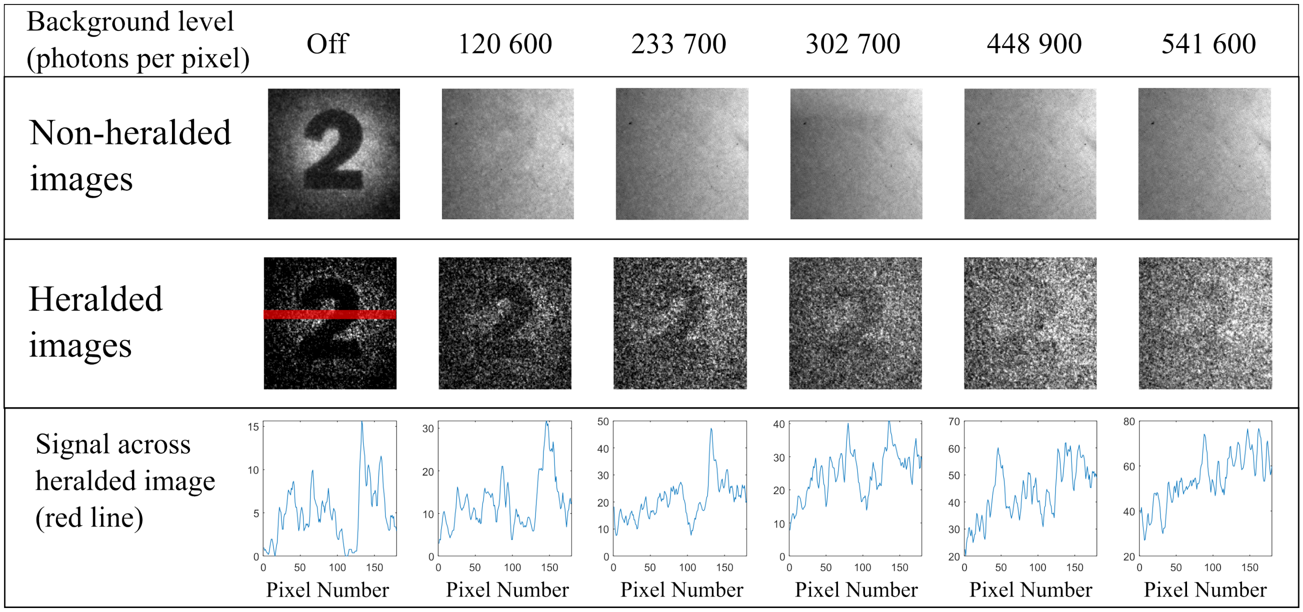

Figure 2. The images produced from our imaging system. The background level was a measurement of the number of photons-per-pixel recorded by the camera when there is no gating of the image. The non-heralded images did not use the temporally correlated photons to trigger the gated intensifier. The heralded images used the heralding signal from a temporally correlated photon to trigger the gated intensifier, this removes background photons from the image acquisition. The red line indicates the area of the heralded image where the signal from the rows were summed and smoothed shown in the lower plots. The plots indicate the magnitude of the signal in comparison to the background light level.

of photon measured by the camera was 63.5 photons-per-second, the resulting image from the 100 exposures contained 6355 photons over the image area. This indicates there was very poor transmission of light through the system. This loss would be due to the poor reflectivity of the DMD, reflection from lenses within the system, and the low quantum efficiency of the camera.

An LED was used to control the level of background light, the voltage supplied to the LED was controlled via a DAC and calibrated to give a linear change in photon number. The images acquired via the non-heralding and heralding methods, with increasing levels of background photons, are presented in figure 2. The non-heralded images used an open gate, such that the image was acquired constantly. The non-heralding image can be shown to quickly be no longer visible within the background photons. The heralded image used the triggering from the SPAD to acquire the image of the temporally correlated photon. To identify where the projected image was no longer discernible from background noise, an area on the heralded image was examined (marked in red), a sum of 15 rows of pixels were summed and smoothed to give the graphs showing the signal across the heralded image. As is shown in the bottom plots, at the highest background level there is almost no dip in the signal relating to the image and hence the limitation of using heralding to reject the background photons had been reached.

The measured signal from the photons source was 6335 photons over the 100 second exposure image. Over the whole image area this gave a signal-photon level of 0.195 ph/pix (photons-per-pixel), within the centre of the image there was a higher intensity and at this location the signal-photon level was 0.426 ph/pix. As the image became fully obscured at the highest illumination level, we could measure the number of photons in that background and calculate how visible the object was with respect to the background. When heralding was used the highest background was measured to be 1.77 ph/pix, this was 4.15 times higher than the photon-source flux. The background seen by the camera without gating was measured with a reduced exposure time (10 µs) such that individual photons could be resolved, and then scaled back up give a background level of 541 600 counts, this was a background reduction of 306 600 times. Given that the gate time is 10 ns it would be expected that the reduction could be 1×10^8, but there was additional triggering within the camera that does not allow every photon to be removed.

Therefore, it has been demonstrated that a photons-source signal of 0.426 ph/pix could be seen within a background of 541 600 ph/pix, therefore the image extraction can produce images with a ratio of 1 272 000 between signal and background illumination. This test is based upon a large image (around 100×100 pixels) and therefore has a high information content for the redundancy of the area.

4. CONCLUSION

We have demonstrated the ability for images to be hidden within background illumination. Using temporally correlated photon-pairs produced from SPDC the image can be extracted from the noise by heralding the signal with one of the photon-pair sending a heralding signal to a gated intensified camera. We have shown that with a background-photon level 1.27×10^6 times higher than the signal-photons the image can still be reconstructed with good visibility. Whilst this result would be dependent upon the image being projected, where higher frequency information would be lost faster, this result is indicative of an experimental system where the rejection of background light is able to be achieved at high levels of background.

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