Quantum imaging with undetected photons

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Information is central to quantum mechanics. In particular, quantum interference occurs only if there exists no information to distinguish between the superposed states. The mere possibility of obtaining information that could distinguish between overlapping states inhibits quantum interference[1,2]. Here we introduce and experimentally demonstrate a quantum imaging concept based on induced coherence without induced emission[3,4]. Our experiment uses two separate down-conversion nonlinear crystals (numbered NL1 and NL2), each illuminated by the same pump laser, creating one pair of photons (denoted idler and signal). If the photon pair is created in NL1, one photon (the idler) passes through the object to be imaged and is overlapped with the idler amplitude created in NL2, its source thus being undefined. Interference of the signal amplitudes coming from the two crystals then reveals the image of the object. The photons that pass through the imaged object (idler photons from NL1) are never detected, while we obtain images exclusively with the signal photons (from NL1 and NL2), which do not interact with the object. Our experiment is fundamentally different from previous quantum imaging techniques, such as interaction-free imaging[5] or ghost imaging[6–9], because now the photons used to illuminate the object do not have to be detected at all and no coincidence detection is necessary. This enables the probe wavelength to be chosen in a range for which suitable detectors are not available. To illustrate this, we show images of objects that are either opaque or invisible to the detected photons. Our experiment is a prototype in quantum information—knowledge can be extracted by, and about, a photon that is never detected.

The conceptual arrangement of our imaging technique, based on a quantum interference experiment[3,4] by Zou, Wang and Mandel, is illustrated in Fig. 1. A pump beam (green) divided by a 50:50 beam splitter (BS1) coherently illuminates two identical nonlinear crystals, NL1 and NL2, where pairs of collinear photons called signal (yellow) and idler (red) can be created ($|c\rangle|d\rangle$ in NL1 and $|e\rangle|f\rangle$ in NL2). The idler amplitude created in NL1 reflects at the dichroic mirror D1 into spatial mode d, and signal amplitude passes into spatial mode c. The idler passes through the object O of real transmittance coefficient T and phase shift γ: $|c\rangle_s|d\rangle_i \rightarrow Te^{i\gamma}|c\rangle_s|d\rangle_i + \sqrt{1-T^2}|c\rangle_s|w\rangle_i$, where for simplicity we lump all lost idler amplitude into a single state $|w\rangle_i$ (here subscripts s and i represent signal and idler). By reflection at dichroic mirror D2, the idler from NL1 aligns perfectly with idler amplitude produced at NL2, $|d\rangle_i \rightarrow |f\rangle_i$. The state at the grey dotted line is thus

$$\frac{1}{\sqrt{2}}\left[\left(Te^{i\gamma}|c\rangle_s + |e\rangle_s\right)|f\rangle_i + \sqrt{1-T^2}|c\rangle_s|w\rangle_i\right] \qquad (1)$$

The idler is now reflected at the dichroic mirror D3 and discarded. The signal states $|c\rangle_s$ and $|e\rangle_s$ are combined at the 50:50 beam splitter BS2. The detection probabilities at the outputs $|g\rangle_s$ and $|h\rangle_s$, obtained by ignoring (tracing out) the idler modes, are

$$P_{g/h} = \frac{1}{2}[1 \pm T\cos\gamma] \qquad (2)$$

Thus, fringes with visibility T can be seen at either output, even though the signals combined at BS2 have different sources[4,10]. These fringes appear in the signal single photon counts; the idlers are not detected. No coincidence detection is required.

The peculiar feature of this interferometer is that no detected photon has taken path d. Yet, in our experiment, it is precisely here where we put the object to be imaged. The key to this experiment is how the signal-source information carried by the undetected idler photon depends on T. For, if $T = 0$, an idler detected after D3, coincident with a signal count at $|g\rangle_s$ or $|h\rangle_s$, would imply the signal source was NL2. Detection of a signal photon without a coincident idler would imply the signal source was NL1. This which-source information destroys interference because it makes the quantum states overlapping at BS2 distinguishable. If $T = 1$, the idler photon carries no which-source information. The signal states overlapped at each output of BS2 are then indistinguishable; thus the interference term in equation (2) appears. The above arguments are valid even though the idler photons are not detected, for it is only the possibility of obtaining which-source information that matters in this experiment.

Our experiment has a connection to interaction-free measurements[11,12]. Note that $P_h = 0$ if no object is placed in the set-up ($T = 1$ and $\gamma = 0$). Now insert an opaque object ($T = 0$) so that $P_h > 0$, and monitor the idler reflection from D3. Coincident counts in $|h\rangle_s$ and the idler detector reveal that the object is present even though no photon interacted with the object. With our set-up it is thus possible to realize non-degenerate interaction-free imaging.

With O and D2 removed, equation (1) would be an ordinary two-particle entanglement[13], $|c\rangle_s|d\rangle_i + |e\rangle_s|f\rangle_i$. With them in, $|d\rangle_i \rightarrow Te^{i\gamma}|f\rangle_i$, which creates equation (1). A normal two-particle entanglement has changed into an interesting single-particle superposition, which is especially rich when T and γ are transverse-position dependent.

We expand the conceptual arrangement of Fig. 1 into an imaging system (Fig. 2). We replace the photon counters with cameras sensitive to single photons and the uniform object with one bearing features, that is, $T = T(x, y)$ and $\gamma = \gamma(x, y)$ depend on transverse position (x, y). Our source produces spatially entangled photon pairs[14,15]. Sharp spatial correlations between signal and idler in the object plane and confocal lens systems[16] (see Methods) guarantee a point-by-point correspondence between the object plane and the detector surface on the camera.

The intensity image (non-constant transmittance) is due to transverse-position-dependent which-source information carried by the undetected idler photons. The phase image is of a different nature: it is due to the fact that the position-dependent phase shift on the idler photons in path d is actually passed to the signal; that is[17], $|c\rangle_s\left(Te^{i\gamma}|f\rangle_i\right) + |e\rangle_s|f\rangle_i = \left(Te^{i\gamma}|c\rangle_s + |e\rangle_s\right)|f\rangle_i$. Remarkably, the idler beam $|f\rangle_i$ alone does not even carry the phase pattern, and without detection in coincidence it could not be used to obtain the phase image[18,19].

We will now show images obtained by detecting 810-nm photons with a camera capable of single-photon sensitivity at this wavelength, when three different objects are illuminated by 1,550-nm photons, to which our camera is blind (see Methods). First, a cardboard cut-out placed into the path D1–D2 is imaged. Next, we show that a position-dependent phase shift produces an image even when the object is opaque (an etched silicon plate) or invisible (etched silica plate) at the detection

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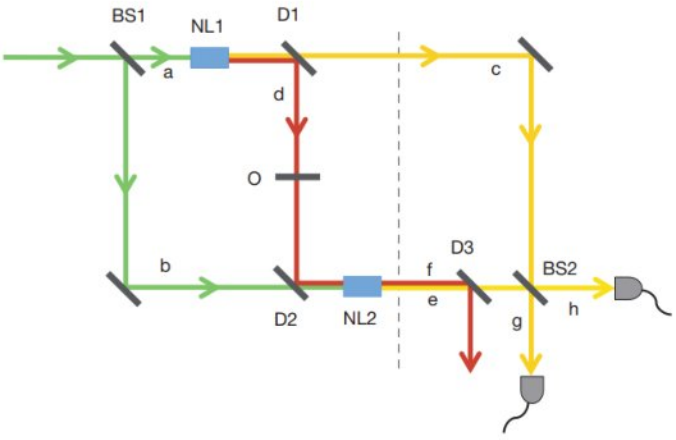

Figure 1 | Schematic of the experiment. Laser light (green) splits at beam splitter BS1 into modes a and b. Beam *a* pumps nonlinear crystal NL1, where collinear down-conversion may produce a pair of photons of different wavelengths called signal (yellow) and idler (red). After passing through the object O, the idler reflects at dichroic mirror D2 to align with the idler produced in NL2, such that the final emerging idler $|f\rangle_i$ does not contain any information about which crystal produced the photon pair. Therefore, signals $|c\rangle_s$ and $|e\rangle_s$ combined at beam splitter BS2 interfere. Consequently, signal beams $|g\rangle_s$ and $|h\rangle_s$ reveal idler transmission properties of object O.

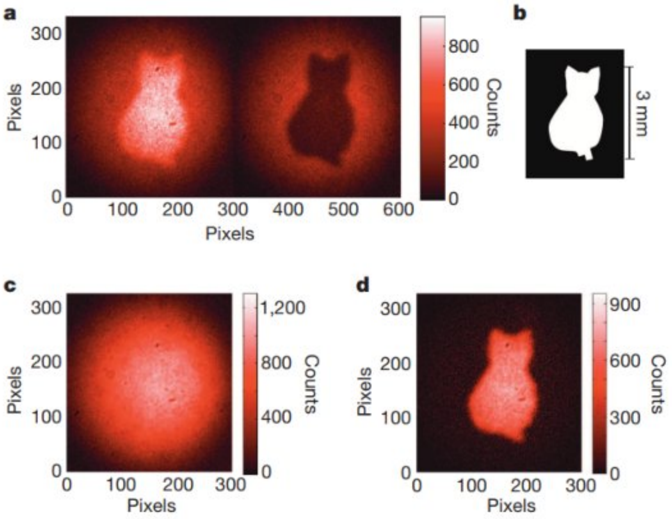

Figure 3 | Intensity imaging. a, Inside the cat, constructive and destructive interference are observed at the outputs of BS when we placed the cardboard cut-out shown in **b** in the path D1–D2. Outside the cat, idler photons from NL1 are blocked and therefore the signals do not interfere. **c**, The sum of the outputs gives the intensity profile of the signal beams. **d**, The subtraction of the outputs leads to an enhancement of the interference contrast, as it highlights the difference between constructive and destructive interference.

wavelength. The images obtained with an electron multiplying charge coupled device (EMCCD) camera show single (non-heralded) counts per pixel (16 μm × 16 μm) obtained in an exposure time of 0.5 s with an electron multiplying gain factor of 20. The visibility achieved in the experiment is 77% (see Methods for details).

Figure 3a shows the beamsplitter output when a cardboard cut-out (illustrated in Fig. 3b) is inserted in the path D1–D2. Constructive interference is seen at one output of the beam splitter and destructive interference is observed in the other output. Interference only occurs in the region corresponding to the idler beam transmitted through the shape cut out of the cardboard, as seen in the sum and difference of the complementary images, shown in Fig. 3c and d, respectively. The sum of the two outputs of the beamsplitter gives the featureless intensity profile of the signal beams, demonstrating that the signal beams, while carrying the intensity information, are not absorbed at all by the mask.

In Fig. 4a, we show the image of an etched 500-μm-thick silicon plate; the plate is shown in Fig. 4b (see Methods section for details of the silicon plate and the etching process). Silicon is opaque to illumination at 810 nm, thus it is impossible to realize transmission imaging by illuminating the silicon with 810-nm photons. However, silicon is highly transparent at 1,550 nm and when we place the object in path D1–D2, the difference in optical path length for the etched and non-etched regions corresponds to a relative phase shift of π. Even though our camera is blind to 1,550-nm light, the image is seen by detecting 810-nm photons at the output of BS2 (Fig. 4a).

Finally, Fig. 5a shows the image of a fused silica (SiO$_2$) plate etched with a pattern that is invisible at the detection wavelength (details are given in the Methods section). We take advantage of the flexibility of our source to obtain collinear non-degenerate down-conversion at 820 nm

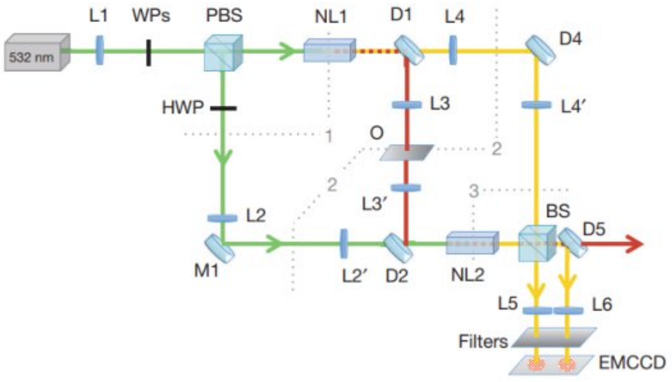

Figure 2 | Experimental set-up. A continuous-wave 532-nm laser (green) illuminates crystals NL1 and NL2. Wave plates (WPs) adjust the relative phase and intensity of the outputs of the polarizing beam splitter (PBS). The dichroic mirror D1 separates down-converted 810-nm (yellow) and 1,550-nm (red) photons. The 1,550-nm photons are transmitted through the object O and sent through NL2 by dichroic mirror D2. Lenses image plane 1 onto plane 3, and plane 2 onto the EMCCD camera. A 50:50 beam splitter (BS) combines the 810-nm beams. Dichroic mirrors D1, D2, D4 and D5 transmit the pump.

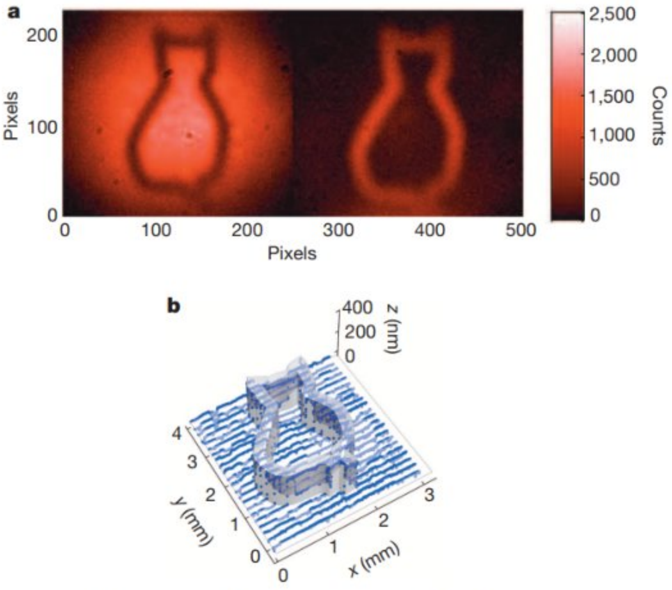

Figure 4 | Phase image of an object opaque to 810-nm light. a, Detection of 810-nm photons at both outputs of BS when a silicon plate (opaque to 810-nm light) with a 3-mm-tall etched cat (**b**) was introduced in path D1–D2. **b**, Three-dimensional rendering of the etch design overlaid with stylus profilometer scans (blue points) of the actual etch depth.

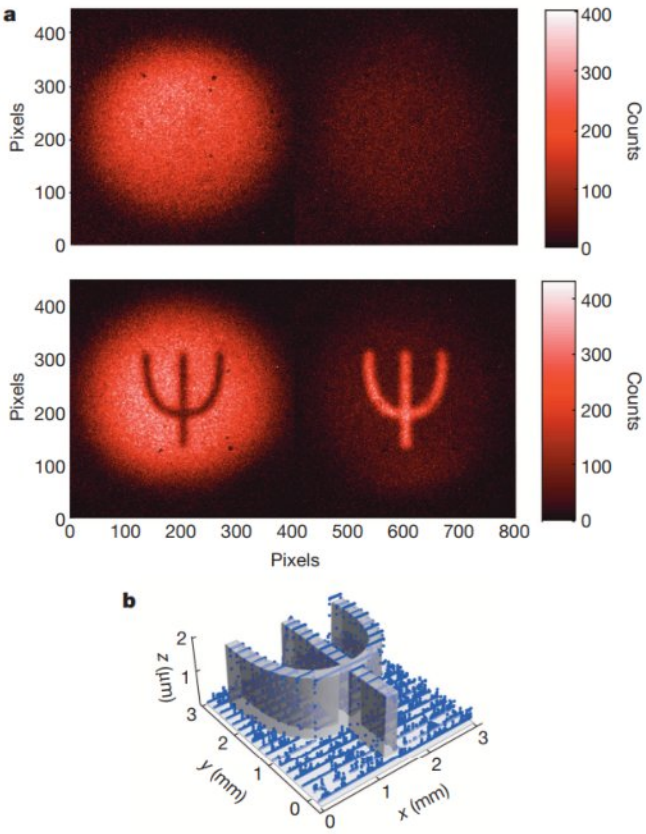

Figure 5 | Phase imaging of a 2π step at 820 nm. a, The top picture was taken with the object (shown in **b**) placed in the 820-nm beam between L4 and L4′; in the bottom picture, the object was placed in the 1,515-nm beam in path D1–D2. **b,** Three-dimensional rendering of the design overlaid with stylus profilometer scans (blue dots) of the actual etch depth.

and 1,515 nm (see Methods). The object (Fig. 5b) has an etch depth of 1,803 nm, imparting a relative phase shift of ~2π for 820-nm light. Thus the object is invisible when placed in the path of the detected photons between L4 and L4′ (top of Fig. 5a). This same etch depth gives an ~π phase step for 1,515-nm light, so when this same object is placed in the path D1–D2 of undetected photons, an image seen in the contrast of constructive to destructive interference is retrieved in the 820-nm outputs (bottom of Fig. 5a).

In summary, we have presented a quantum system for intensity and phase imaging where the photons that illuminate the object are not detected and the photons that are detected do not illuminate the object. We image objects that are either opaque or invisible at the detection wavelength (near-infrared) by illuminating three different objects with a wavelength to which our detector is blind. This experiment is fundamentally different to ghost imaging[6–9] as it relies on single-photon interference and does not require coincidence detection. Furthermore, our technique could be used for non-degenerate interaction-free imaging, with potential applications spanning biological imaging to the inspection of integrated circuits. Our system can realize grey-scale intensity or phase imaging, and it can be modified in order to measure spectral features (spectral imaging)[20].

We have demonstrated that our technique does not require the laser or the detector to function at the same wavelength as that of the light probing the object. Additionally, any nonlinear process can be used as a source, and this provides flexibility in the wavelength range for both detection and illumination of the object. In particular, in spontaneous parametric down-conversion (as used here), the only absolute restriction is that the sum of the two photon energies equals that of the pump photons. We have shown that information can be obtained about an object without detecting the photons that interacted with the object. Knowing the two-photon state, one can obtain information about an object. It has not escaped our attention that, on the other hand, by knowing the object, one could obtain information about the quantum state without detecting it.

METHODS SUMMARY

A detailed schematic of our imaging set-up is shown in Fig. 2. A 532-nm linearly polarized Gaussian pump laser beam focused by lens L1 on plane 1 is divided at a polarizing beam splitter (PBS) and coherently illuminates two identical periodically poled potassium titanyl phosphate (ppKTP) crystals, NL1 and NL2. The PBS plus wave plates (WPs) are used to control the relative amplitudes and phases between the reflected and transmitted pump beams. With an extra half-wave plate (HWP) in the reflected beam, both beams have the same polarization. The 1,550-nm idler amplitude produced at NL1 is reflected by dichroic mirror D1, through which the 810-nm signal and the pump are transmitted. Dichroic mirror D4 transmits 532-nm light and reflects 810-nm light. A long-pass filter (not shown in the figure) placed directly before the object O blocks any residual 532-nm or 810-nm light. The 1,550-nm amplitude from NL1 illuminates the object O and is then overlapped with the pump beam at dichroic mirror D2 that transmits 532-nm light and reflects 1,550-nm light.

Lens pairs L2–L2′, L3–L3′, and L4–L4′ image plane 1 onto plane 3, thereby ensuring that pump, idler and signal, respectively, are identical in these planes, thus contributing to obtain high interference visibility[21] (see Methods). Lenses L5 and L6 together with L3′ and L4′ image object plane 2 onto the camera surface.

The 810 ± 1.5 nm photons are detected (without heralding) in both outputs of the BS using an EMCCD camera that exhibits single-photon sensitivity at 810 nm, but has a negligible response at 1,550 nm.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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