Ghost Imaging in Time

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Ghost imaging is a novel technique that produces the image of an object by correlating the intensity of two light beams, neither of which independently carries information about the shape of the object[1,2]. Ghost imaging has opened up new perspectives to obtain highly-resolved images[3], even in the presence of noise and turbulence[4]. Here, exploiting duality between light propagation in space and time[5], we demonstrate the temporal analogue of ghost imaging. We use a conventional fast detector that does not see the temporal 'object' to be characterised, and a slow integrating 'bucket' detector that does see the object but without resolving its temporal structure. Our experiments achieve temporal resolution at the picosecond level and are insensitive to temporal distortion that may occur after the object. The approach is scalable, can be integrated on-chip, and offers great promise for dynamic imaging of ultrafast waveforms.

Ghost imaging uses correlation measurement between light transmitted through (or reflected by) an object and the spatially-resolved intensity pattern of the incident light to reconstruct the ghost image of the original object[1]. The principle of spatial ghost imaging is illustrated in Fig. 1(a). The beam from a light source with spatially random intensity pattern is divided between two paths. In one arm (test), the random incident light directly illuminates the object with the scattered light collected by a single-pixel bucket detector which produces only a spatially-integrated signal. In the second arm (reference), the incident light does not see the object at all, but the random fluctuations in the beam are measured as a function of spatial position with a high-resolution Charge-Coupled Device (CCD) camera. Neither of the detectors alone can produce an image of the object – yet by correlating the two measurements from the bucket and high-resolution detectors over multiple intensity patterns produced by the source, the object appears like a ghost in the focus plane of the camera. The essential nature of ghost imaging lies in the mutual spatial correlation of the two beams, which may be quantum or classical. Various light sources can be used including spatially-entangled photon sources[2,6–9], classical light sources[2,10–15], or structured light fields programmed by a spatial light modulator to minimise the number of measurements in the time series to obtain an accurate representation of the object[16].

Many propagation effects in optics first seen in the spatial domain have subsequently been observed in time, exploiting space-time duality - the correspondence between the diffraction of a light beam and the dispersive propagation of a short optical pulse[17–19]. Recently, this duality has successfully enabled major advances in the processing of time-varying signals including all-optical magnification of ultrafast data rates by a thousand fold[20,21], all-optical correlation[5], real-time detection of single-shot spectra at hundreds of MHz speed[22], or temporal cloaking[23]. It has also been suggested theoretically[24] and numerically[25] that this duality may allow the transposition of the concept of ghost imaging to the temporal domain. Here, we confirm this proposal experimentally, demonstrating how intensity correlation measurements from a temporally fluctuating light source allow retrieval of a rapidly varying temporal object that modulates the amplitude of the transmitted or reflected light.

We implement temporal ghost imaging using an optical fibre-based system shown in Fig. 1(b). The random intensity fluctuations of a laser diode replace the beam with a randomly fluctuating transverse intensity pattern, and the temporal intensity modulation of the incident light field imposed by an ultrafast optical modulator replaces the scattering from a spatial object. In this sense, the 'random illumination' used in the ghost imaging arises from the intrinsic randomness in the temporal fluctuations of the light emitted by the laser diode, a quasi-continuous multimode laser operating at $\lambda = 1547$ nm. The bandwidth is $\Delta\lambda = 0.6$ nm, resulting in random intensity fluctuations with a characteristic time $\tau_{\rm c} = \lambda^2/(c\,\Delta\lambda) \approx 13$ ps where c is the speed of light in vacuum. At the output of the source, the intensity is equally divided between the test and reference arms with a 50/50 fibre coupler which replaces the beam splitter in the spatial setup. In the reference arm, the temporal fluctuations of the source are measured with a 25-GHz photodiode and a 20-GHz real-time oscilloscope, which results in an effective fluctuation time $\tau_{\rm c}^{\rm eff} = 50$ ps. Multiple series of intensity fluctuations measured from the reference arm and recorded over a 2-ns time window are plotted in Fig. 2. One can clearly observe the random fluctuations of the intensity with an effective characteristic time of approximately 50 ps. We can also see that the intensity of the source averaged over a large series of consecutive 2-ns segments is constant, which ensures that the retrieved ghost image is directly proportional to the object[24] (see also Methods). In the test arm, the temporal object is a bit sequence generated by an ultrafast electro-optic modulator (EOM) driven by a 10 Gb/s pulse pattern generator which temporally modulates ('scatters') the randomly fluctuating light (see Methods). The light transmitted through the object is detected by a slow photodiode with 5-ns response time, which is too slow to resolve the temporal structure of the bit sequence.

The normalised intensity correlation function $C(t)$ (i.e. the ghost image) calculated over a series of time signals measured simultaneously from both arms is defined by:

$$C(t) = \frac{\langle \Delta I_{\rm ref}(t) \cdot \Delta I_{\rm test} \rangle_N}{\sqrt{\langle [\Delta I_{\rm ref}(t)]^2 \rangle_N \, \langle [\Delta I_{\rm test}]^2 \rangle_N}}. \tag{1}$$

Here, $I_{\rm ref}(t)$ represents the time-resolved intensity measurement from the reference arm at time t and $I_{\rm test}$ is the integrated intensity from the test arm. $\langle\,\rangle_N$ denotes ensemble average over a series of N realisations, and $\Delta I = I - \langle I \rangle_N$. Figure 3 shows the ghost image obtained from a series of $N = 80\,000$ realisations where the temporal intensity fluctuations of the light source follow a random pattern in each of the realisations. The agreement with the direct image of the object measured with the fast detector is remarkable. Specifically, the temporal object (the transmission of the EOM driven by the bit sequence) is precisely reproduced both in terms of duration and amplitude.

The performance of the ghost imaging system can be characterised by (i) the temporal resolution and (ii) the signal-to-noise ratio (SNR). The temporal resolution directly corresponds to the effective fluctuation time (i.e. the maximum value between the coherence time of the source and the response time of the fast detector/oscilloscope – see Methods), which must then be shorter than the object variations that one wants to resolve. The noise in the measurement mainly arises from the standard error of the correlation function calculated from a finite number of realisations and the SNR is given by[26]:

$$\mathrm{SNR}(t) = \frac{C(t)\,\sqrt{N}}{1 - C^2(t)}, \tag{2}$$

assuming that the noise from the detectors is negligible. The SNR is therefore expected to increase with the number of realisations and this is shown in Fig. 4(a-d) (see also the movie in the Supplementary Material for a full evolution of the ghost image as a function of the number of realisations). Note that the amplitude of the ghost image should be independent of the number of measurements, which can be readily observed in the figure. For a fixed number of realisations, the SNR can be improved by increasing the effective fluctuation time of the source. In practice, this can be done in two different ways, depending on which parameter limits the value of $\tau_{\mathrm{c}}^{\mathrm{eff}}$: either by increasing the coherence time of the source or by decreasing the fast detector bandwidth. As a rule of thumb, in order to obtain a ghost image at fast acquisition rates, yet with a high temporal resolution and optimum SNR, the effective fluctuation time should be equal to half of the fastest time variations that one wants to resolve in the object (Nyquist criterion). For the 100-ps bits that constitute the object here, the effective fluctuation time for optimum SNR and acquisition time is then 50 ps. Lower values may improve the temporal resolution at the expense of the SNR whilst higher values will result in the opposite. Ghost images recorded for a fixed number of measurements (N = 5 000) with the detection bandwidth in the reference arm decreasing from 20 to 3 GHz (and thus the effective fluctuation time increasing from 50 to 300 ps) are shown in Fig. 4(e-h). One can clearly see how the SNR is improved as the effective fluctuation time is increased but that this improvement occurs at the expense of temporal resolution in the ghost image.

Ghost imaging is inherently insensitive to distortion that may occur between the object and the bucket detector. This remarkable particularity has attracted considerable attention in the spatial domain with the possibility of performing high resolution imaging even in the presence of a strong scattering medium or atmospheric turbulence when any direct measurement would result in a poor-quality image. This particularity also applies in the time domain and we demonstrate that the technique allows overcoming the distortion experienced by the modulated light field after the temporal object. For this purpose, a 29-m multimode fibre is inserted after the EOM, which strongly distorts the bit pattern. The results in Fig. 5 clearly show how the intermodal dispersion accumulated in the multimode fibre severely distorts a direct measurement of the temporal object performed with a fast detector. But when the ghost imaging technique is used, the distortion is washed out and it has no influence on the quality of the ghost image. More generally, ghost imaging in the time domain allows compensating for arbitrary distortion experienced by a temporal object provided the integrated transmitted intensity does not vary over the total acquisition time.

These experiments represent the first demonstration of ghost imaging in the time domain. Using an all-fibre setup and a laser source with random intensity fluctuations, our results illustrate how an ultrafast temporal object with structure on a scale of 10 Gb/s can be measured with $\sim$ 50 ps temporal resolution without directly detecting the object. The technique can be adapted to the detection of all-optical data streams by modulating the temporal fluctuations of the light source through e.g. four-wave mixing in a nonlinear fibre. The system is scalable to any data rate and shape by adapting the coherence time of the source. Adjusting the fast detector bandwidth and number of distinct measurements allows for optimising the measurement speed and SNR. We also emphasise that a quantum version of the temporal ghost imaging system can be implemented using entangled photon pairs. The setup can also be modified to include a time lens[27] in the reference arm and thereby magnify the ghost image[24]. Our results open novel perspectives for dynamic imaging of ultrafast waveforms when the waveform has been severely distorted by the transmission medium, in the presence of high noise or low signal strength, and we anticipate applications in communications, remote sensing and ultrafast spectroscopy.

Fig.1. Comparison between spatial (left) and temporal (right) ghost imaging experimental setups.

Fig.2. Measured intensity fluctuations of the multimode laser source. A single realisation (black) is shown together with 50 other realisations (grey). The average intensity of 5 000 realisations is shown as the red line.

Fig.3. Comparison between the ghost image (black) and direct image measured with the fast detector (red). The bandwidth of the detection is equal to 20 GHz, corresponding to an effective fluctuation time of 50 ps. The number of realisations in the measurement series for the ghost image is equal to N = 80 000.

Fig.4. Ghost image as a function of the number of realisations and effective fluctuation time. In figures (a-d) the number of realisations N increases from 1 000 to 80 000, and in figures (e-h) the effective fluctuation time τ_c^{eff} increases from 50 to 300 ps, as indicated. The temporal object is identical to that in Fig.3.

Fig.5. Comparison between the ghost image (in black) and the direct image (in green) in the presence of strong dispersion experienced by the object in a multimode fibre added between the EOM and the detector. For comparison, the direct image obtained without the multimode fibre is also shown in red. Both direct measurements are performed with the fast detector. The bandwidth of the detection is equal to 20 GHz, corresponding to an effective fluctuation time of 50 ps. The number of realisations in the measurement series for the ghost image is equal to N = 100 000.

Methods

In our experiments, the object is created by a zero-chirp 10-GHz bandwidth electro-optic modulator (Thorlabs LN81S-FC) driven by a pulse pattern generator (Advantest D3186). The 10-GHz clock signal was generated by a microwave signal generator (Rohde & Schwarz SMR20) resulting in bits of 100-ps duration. The detector in the test arm is a 1.2-GHz InGaAs photodiode (Thorlabs DET01CFC). Its response is integrated over 5 ns, such that the effective bandwidth is equal to 0.2 GHz only. The detector in the reference arm measuring the intensity fluctuations of the source is a 25-GHz UPD-15-IR2-FC InGaAs photodiode (ALPHALAS). The oscilloscope is a 20-GHz, 50-Gsamples/s real-time oscilloscope (DSA72004 Tektronix). The object was repeated periodically with a period of 50 ns. As a result, the data acquisition time required for 100 000 realisations is of the order of 5 ms only.

The coherence time τ_c of the source corresponds to the characteristic time of its intensity fluctuations. If the response time τ_{det} of the fast detection device (detector + oscilloscope) in the reference arm is shorter than τ_c (i.e. if the detection device can resolve the fluctuations of the source), then the temporal resolution of the ghost imaging process is equal to τ_c and object details that are faster that τ_c cannot be resolved. On the other hand, if τ_{det} is longer than τ_c (as it is the case in our experiments), then the characteristic time of the intensity fluctuations that are effectively recorded by the detection device is $\tau_c^{eff} \sim \tau_{det}$ ($> \tau_c$), and the temporal resolution of the ghost imaging process is thus given by τ_{det}. In other words, the temporal resolution is set by τ_c^{eff}, which is the maximum value between τ_c and τ_{det}.

In order to have a direct correspondence between the correlation and the original object it is important that the intensity fluctuations averaged over the number of realisations is constant over the measurement time window of a single realisation. This condition is generally fulfilled in the case of a quasi-CW light source but does not hold if one uses a pulsed light source. In this latter case, the temporal object would be distorted by the time variation of the average intensity (or average pulse shape)[24].

All the fibres are SMF-28 patch cords of 1-m length with dispersion parameter of 18 ps/(nm.km) at 1550 nm, except the multimode fibre used to add distortion, which is a 29-m FG105LCA fibre. Due to the fact that the SMF-28 fibres are short, the dispersion accumulated during the propagation from the source to the fast detector on the one hand, and from the source to the object (EOM) on the other hand, is negligible. That is why no temporal lens is needed to perform the imaging process – and the magnification factor between the object and the ghost image is simply equal to 1. This situation is equivalent in the spatial case to the near-field regime as described in Ref. 11.

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