Demonstration of temporal cloaking

Moti Fridman1, Alessandro Farsi1, Yoshitomo Okawachi1 & Alexander L. Gaeta1

Recent research has uncovered a remarkable ability to manipulate and control electromagnetic fields to produce effects such as perfect imaging and spatial cloaking1–14. To achieve spatial cloaking, the index of refraction is manipulated to flow light from a probe around an object in such a way that a ‘hole’ in space is created, and the object remains hidden1–14. Alternatively, it may be desirable to cloak the occurrence of an event over a finite time period, and the idea of temporal cloaking has been proposed in which the dispersion of the material is manipulated in time, producing a ‘time hole’ in the probe beam to hide the occurrence of the event from the observer15. This approach is based on accelerating the front part of a probe light beam and slowing down its rear part to create a well controlled temporal gap—inside which an event occurs—such that the probe beam is not modified in any way by the event. The probe beam is then restored to its original form by the reverse manipulation of the dispersion. Here we present an experimental demonstration of temporal cloaking in an optical fibre-based system by applying concepts from the space–time duality between diffraction and dispersive broadening16. We characterize the performance of our temporal cloak by detecting the spectral modification of a probe beam due to an optical interaction and show that the amplitude of the event (at the picosecond timescale) is reduced by more than an order of magnitude when the cloak is turned on. These results are a significant step towards the development of full spatio-temporal cloaking.

The detection of an object or an event is often performed by measuring a change in the properties of a light probe that interacts with the object or with elements participating in the event. The idea of spatial cloaking consists of the probe light being bent in a precise fashion to prevent it from being scattered by the object, which thus remains hidden from an observer. This has been done typically through use of exotic materials, such as ones with a negative index of refraction or through sophisticated manipulation of the refractive index17,18. Analogously, it could be possible to cloak an event in the time domain from an observer by manipulating the dispersion of a material such that a temporal gap is created in the probe beam: any event that occurs within this gap does not modify the temporal/spectral properties of the probe beam and thus remains undetected15. This requires rapid changes in the dispersion and a recently proposed approach19 involves the use of optical fibres that are pumped to high power levels to produce large changes in the intensity-dependent refractive index. However, at such powers, other optical processes such as stimulated Raman and Brillouin scattering could limit the ability to achieve cloaking. We propose an alternative means of creating the conditions that allow for temporal cloaking in which we apply concepts from the space–time duality associated with diffraction and dispersion17.

The space–time duality represents the analogy between diffraction and dispersion that arises from the mathematical equivalence between the equations describing the diffraction of a beam of light and the one-dimensional temporal propagation of a pulse through a dispersive medium17–18. Similar to a spatial lens that imparts a quadratic phase shift in space, a time-lens can be implemented that produces a quadratic phase shift in time9–21. This time-lens can, for example, magnify20 or compress3 signals in time and obey an equivalent of the lens law. Time-lenses can be created with an electro-optic modulator18 or via a parametric nonlinear optical process such as four-wave mixing with a chirped pump wave19,22.

To produce the time gap necessary to achieve temporal cloaking, we create a temporal element that imparts a suitable nonlinear frequency chirp on a probe beam over a time window in which the gap will be produced. After propagating through a dispersive element, the different frequency components of the probe beam are advanced and retarded as required to produce the desired temporal gap. We create such a temporal element by implementing a split time-lens (STL) which is composed of two half time-lenses connected at the tips. This temporal element is created by the nonlinear process of Bragg scattering via four-wave mixing with two pump waves in which the wavelength of one pump wave is constant in time and the other pump wave is pulsed and has a linear frequency chirp. To produce the appropriate chirp on the pump wave that will lead to a temporal gap, the red and blue spectral components of the pump pulse are separated and delayed with respect to each other. It is this step that splits the time lens to create the STL, and further details of how this is accomplished and modelled are provided in the Supplementary Methods.

A schematic of the full temporal cloaking device is presented in Fig. 1. A continuous-wave probe beam, which could be used to detect an event, is incident from the left. After passing through the STL the light propagates through a dispersive element (for example, a single-mode fibre) that translates the red and blue parts of the chirped probe to the edges of the time window, creating a temporal gap in the probe beam so that any event that might lead to a temporal or spectral change during this window will have no effect, and the event will remain undetected. Finally, a medium with a dispersion opposite in sign to the previous element (for example, a dispersive-compensating optical fibre), together with a second, similar STL, closes the gap so that neither the occurrence of the event nor the presence of the time-lenses are detected. (We note that the spatial equivalent to this second negative dispersive element would be one that produces negative diffraction19 and thus would require a metamaterial with a negative index of refraction.)

The actual experimental configuration for temporal cloaking is presented in Fig. 2. We numerically simulated the probe beam as it passes through a pair of STLs, which are used to create a temporal ‘hole’ in a probe beam such that any temporal or spectral changes caused by an event within this hole do not occur. The figure is oriented such that the probe light is described by horizontal lines and lines at different orientations represent different wavelengths. D denotes the magnitude of the total negative or positive group-velocity dispersion.

1School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA.

©2012 Macmillan Publishers Limited. All rights reserved
through the system by solving the nonlinear Schrödinger equation. The resulting wavelength of the probe beam as a function of time before and after the STL is shown in Fig. 2a and b, respectively. The light then propagates through a dispersive element consisting of a single-mode fibre such that the shorter (or longer) wavelengths propagate faster (or slower) than the initial probe beam wavelength. The wavelength distribution as a function of time shown in Fig. 2b becomes that shown in Fig. 2c, in which a temporal gap opens at the focal point of the STL. The gap is synchronized such that the event occurs within this gap and therefore is not sensed by the probe. The probe then propagates through a dispersion-compensating fibre, and the temporal gap is closed as shown in Fig. 2d. Finally, a second STL restores the probe light back to its initial wavelength, shown in Fig. 2e, so that the probe beam is restored to its initial state, and both the event and the presence of the time-lenses are undetected. We note that both after the time-lenses and after the event, we remove the pump waves from the system with wavelength division multiplexers.

Figure 3 shows experimental data illustrating how a temporal gap is created in a probe beam at 1,542 nm. Using a tuneable narrow-band filter followed by a fast (30 GHz) photo-detector connected to a sampling scope, we measured the exact time for each wavelength to obtain a spectrogram of the probe beam, after the first STL (blue dots), after the single-mode fibre at the focal length of the STL (red circle), and after the dispersion-compensating fibre before the second STL (green asterisks). After the first STL the probe acquires a frequency chirp, illustrated in Fig. 2b. After the single-mode fibre the higher wavelengths are delayed while the lower wavelengths are advanced so that a temporal gap opens from −25 ps to 25 ps according to Fig. 2c. This gap is closed after the dispersion-compensating fibre, and the frequency chirp returns to that shown in Fig. 2d. Before the first STL and after the second STL we detect only the probe at its original wavelength. The inset shows the power of the probe beam as a function of time when the gap is opened (red) and after the gap is closed (green), which provides additional evidence that during the temporal gap the power of the probe beam is significantly lower and that after closing the gap, no appreciable disturbance is observed.

To demonstrate the temporal cloaking capability of this system, we create an event that results in the generation of new frequencies due to the presence of the probe beam. It consists of a nonlinear interaction of a short pump pulse with a probe beam via four-wave mixing with a repetition rate of 41 kHz. When the cloak is off, the probe beam at 1,569 nm interacts in a highly nonlinear fibre with a short (5 ps) pump at 1,554 nm such that a frequency component is generated at 1,539 nm every 24 μs. Thus, the signature of the event is the detection of the 1,539 nm signal, and when the cloak is turned off, it is clearly observed, as shown in Fig. 4a by the dashed (blue) curve. However, when the cloaking is turned on, the amplitude of the detected signal is reduced below the detection noise level, as shown in Fig. 4a (solid red curve) for several interaction events. The spectrum of the output signal in the regime near the idler wavelength is presented in Fig. 4b when the event is uncloaked (blue), when the event is cloaked (red), and without the event (green). To investigate the cloaking efficiency further, in Fig. 4c we present the signal without the event (green) and with the event when the cloaking is off (solid blue curve) and on (red dots) using a highly sensitive detector with a 300-MHz bandwidth. When the cloaking is on, the detected amplitude of the event is more than ten times lower than when the event is uncloaked.

Finally, we investigate the efficiency of the cloak as a function of the pump power of the STLs by measuring the amplitude of the detected event as a function of the pump power used by both STLs. The pump power of the STLs governs the amount of light in the probe beam that is shifted in frequency, so as the pump power increases, less light remains in the probe beam during the temporal gap when the event occurs (see Fig. 5). When the average pump power is 17 mW, the amplitude of the detected signal is 6.1 mV (also shown in the upper inset). As the pump power is increased, the detected amplitude decreases until it reaches the noise level at 2.3 mV (shown in the lower inset), when the pump power of the STL is 37 mW. Increasing the pump power of the STLs further increases the amplitude due to higher pump noise. Using numerical simulations of the propagation of the
Figure 4 | Experimental results of the temporal cloaking. Experimental results showing the detection of signal, indicating that the probe beam has undergone an interaction (that is, an event) with a short pump pulse. a. The events occur every 24 μs when the cloaking is turned off (dashed blue curve) and on (solid red curve). When the cloaking is turned on, the amplitude of the signal probing the event is below the detection noise level, indicating that the event has been hidden. b. Spectra of the output signal around 1,539 nm as generated from the four-wave-mixing event when the event is uncloaked (blue), when the event is cloaked (red) and without the event (green). c. Temporal measurement of an uncloaked event (blue), cloaked event (red), and without an event (green). The amplitude of the event is more than ten times smaller when the cloaking is on, and the probe beam is nearly identical to that without an event.

signal through our cloaking system, we can predict the output signal amplitude as a function of pump power for our system. The results are presented as the solid blue curve in Fig. 5 and show good agreement with the experimental results. A detailed description of the numerical model is presented in the Supplementary Information.

The temporal gap can be readily widened by increasing the dispersive broadening of the pump and the dispersion between the STLs. However, as the dispersion is increased, effects due to third-order dispersion arise, which will prevent the gap from closing completely unless the third-order dispersion is compensated. In our experiment, the spectral and temporal width of the pump pulses before chirping are 9 nm and 0.4 ps, respectively, which results in third-order dispersion limiting the width of the temporal gap to 110 ps, as long as the pump power is increased to efficiently deplete the probe beam completely within the gap. Nevertheless, given that the third-order dispersion is proportional to Δλ² whereas the amount of linear frequency chirp is proportional to Δλ (ref. 16), it is possible to increase the temporal gap by resorting to narrower pump pulses and introducing more dispersion. The limitation in this case is stimulated Brillouin scattering, which limits the length of the single-mode fibre to 50 km and the temporal gap to a width of a few nanoseconds.

Our results could also find application beyond full spatial temporal cloaking. Although spatial cloaking is still limited in angular acceptance, wavelength, polarization and efficiency, we have shown that we can deplete a probe wave and restore it to its original state after the event. This suggests it is possible to use similar technology for routing different optical data streams coming simultaneously into a single optical data processing unit by opening a gap in one of the data streams and restoring it to a different time so that it will arrive after the other stream has been processed.

In summary, we have presented the first experimental demonstration of temporal cloaking that successfully hides an event from a probe beam in the time domain. Our scheme is based on the space–time duality, using a pair of STLs. The STLs use parametric four-wave mixing such that dispersion manipulation is highly efficient, and can readily be adapted for other wavelengths in the electromagnetic spectrum. Our results represent a significant step towards obtaining a complete spatio-temporal cloaking device.

METHODS

The first STL needs to focus light to the edges of the time window rather than to the centre so that after propagating through a medium with normal group-velocity dispersion, part of the probe light is delayed in time while the other part is advanced. This is realized by imposing a parabolic phase shift with a discontinuity in the middle. To obtain such a STL, we use Bragg scattering via four-wave mixing such that dispersion manipulation is highly efficient, and can readily be adapted for other wavelengths in the electromagnetic spectrum. We use a tuneable continuous-wave laser (SANTAC TSL-210) to generate the probe wave. To generate the pump waves, we use a femtosecond laser based on an erbium-doped fibre ring laser with a carbon nanotube saturable absorber. Both for the STLs and for the four-wave mixing process used to create the event we use a highly nonlinear single-mode fibre from Optical Fiber Solutions in Denmark.

Received 13 June; accepted 1 November 2011.

1. Leonhardt, U. Optical conformal mapping. Science 321, 1777–1780 (2006).
2. Pendry, J. B., Schurig, D. & Smith, D. R. Controlling electromagnetic fields. Science 312, 1780–1782 (2006).
3. Leonhardt, U. & Tyc, T. Broadband invisibility by non-Euclidean cloaking. Science 323, 110–112 (2009).
4. Cai, W., Chettiar, U. K., Kildishev, A. V. & Shalaev, V. M. Optical cloaking with metamaterials. Nature 444, 224–227 (2007).
5. Cummer, S. A. et al. Scattering theory derivation of a 3d acoustic cloaking shell. Phys. Rev. Lett. 100, 024301 (2008).
6. Lai, Y., Chen, H., Zhang, Z. Q. & Chen, C. T. Complementary media invisibility cloak that cloaks objects at a distance outside the cloaking shell. Phys. Rev. Lett. 102, 093901 (2009).
7. Gabrielli, L. H., Cardenas, J., Poitras, C. B. & Lipson, M. Silicon nanostructure cloak operating at optical frequencies. Nature Photon. 3, 461–463 (2009).
8. Li, Valentine, J., Zentgraf, L., Bental, T. G. & Zhang, X. An optical cloak made of dielectrics. Nature Mater. 8, 568–571 (2009).
9. Li, J. & Pendry, J. B. Hiding under the carpet: a new strategy for cloaking. Phys. Rev. Lett. 101, 203901 (2008).
10. Miller, D. A. B. On perfect cloaking. Opt. Express 14, 12457–12466 (2006).
11. Wieder, R. A. Rigorous analysis of high-order electromagnetic invisible cloaks. J. Phys. A 41, 065207 (2008).
12. Greenleaf, A., Lassas, M. & Uhlmann, G. Anisotropic conductivities that cannot be detected by EIT. Physiol. Meas. 24, 413, doi:10.1088/0967-3334/24/2/353 (2003).
13. Schurig, D. et al. Metamaterial electromagnetic cloak at microwave frequencies. Science 314, 977–980 (2006).
14. Chen, H. & Wu, B. I., Zhang, B. & Kong, J. A. Electromagnetic wave interactions with a metamaterial cloak. Phys. Rev. Lett. 99, 063903 (2007).
15. McClintock, M. T., Favaro, A. Kinsler, P. & Boardman, A. A spacetime cloak, or a history editor. J. Opt. 13, 024003 (2011).
16. Agrawal, G. P. *Nonlinear Fiber Optics* 4th edn (Academic Press, 2007).
17. Kolner, B. H. Space-time duality and the theory of temporal imaging. *IEEE J. Quantum Electron.* **30**, 1951–1963 (1994).
18. Kolner, B. H. & Nazarathy, M. Temporal imaging with a time lens. *Opt. Lett.* **14**, 630–632 (1989).
19. Bennett, C. V. & Kolner, B. H. Principles of parametric temporal imaging. I. System configurations. *IEEE J. Quantum Electron.* **36**, 430–437 (2000).
20. Bennett, C. V. & Kolner, B. H. Principles of parametric temporal imaging. II. System performance. *IEEE J. Quantum Electron.* **36**, 649–655 (2000).
21. Salem, R. et al. Optical time lens based on four-wave mixing on a silicon chip. *Opt. Lett.* **33**, 1047–1049 (2008).
22. Foster, M. A. et al. Silicon-chip-based ultrafast optical oscilloscope. *Nature* **456**, 81–84 (2008).
23. Foster, M. A. et al. Ultrafast waveform compression using a time-domain telescope. *Nature Photon.* **3**, 581–585 (2009).

**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

**Acknowledgements** We thank D. J. Gauthier for his comments. This work was supported by the Defence Advanced Research Project Agency and by the Center for Nanoscale Systems, supported by the National Science Foundation for Science, Technology, and Innovation (NYSTAR).

**Author Contributions** M.F., A.F. and Y.O. performed the experiments and the numerical simulations. A.L.G. supervised the project.

**Author Information** Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to A.L.G. (alg3@cornell.edu).