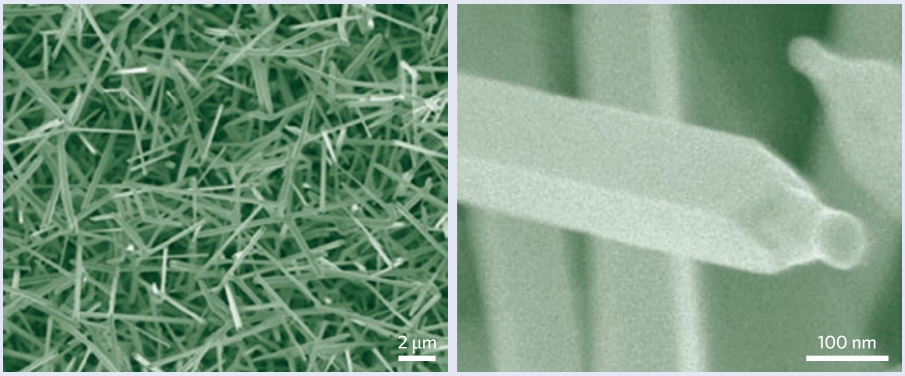
NANOPHOTONICS

Light-emitting indium tin oxide



IOP

Indium tin oxide (ITO) is an important conducting oxide material that is widely used as a transparent electrode in solar cells and flat-panel displays. Usually this material is fabricated as a thin planar film, but in recent years there has been considerable interest in fabricating ITO in the form of nanostructures, especially nanowires, for use in miniature photonic circuitry.

The transparency and conductivity of an ITO nanowire strongly depend on its tin concentration. Unfortunately, however, controlling tin concentration in ITO nanowires is difficult through existing growth techniques. Now, Jing Gao and co-workers from Singapore and China have developed a method of fabricating ITO nanowires that not only provides control over the tin concentration but also introduces light-emitting functionality, which could prove useful for optoelectronic devices (*Nanotechnology* **22**, 195706; 2011).

The single-crystalline ITO nanowires were synthesized through a vapour transport method, in which In_2O_3, SnO_2 and graphite powders were loaded into a horizontal tube furnace. The nanowires were grown at 840 °C in an argon gas atmosphere on a quartz substrate coated with thin sputtered layers of gold, which acted as a catalyst. The fastest nanowire growth was in the [100] direction. The resulting nanowires were approximately 180 nm wide and a few micrometres in length. The atomic doping of tin in the ITO nanowires was tuned in the range of 0–6.4% (atomic, at.%) by controlling the composition of the source materials.

The nanowires were transparent in the visible and near-infrared regions of the electromagnetic spectrum. Their absorption edge shifted from 3.4 eV to 3.8 eV when the tin doping was increased from 3.8 at.% to 6.4 at.%. When the nanowires were excited by a He–Cd laser (wavelength of 325 nm), broad blue emission was observed at around 430 nm. The researchers believe that the light emission was due to the formation of a new defect level induced in the bandgap by the tin doping. A strong and sharp emission peak was observed at 380 nm for ITO nanowires with a tin doping of 3.8 at.%. The temperature dependence of the photoluminescence revealed the existence of bound exciton complexes around 3.36 eV below 100 K. The researchers also demonstrated the epitaxial growth of vertically aligned ITO nanowires on an α-cut sapphire substrate. X-ray diffraction measurements showed that the epitaxial growth direction of ITO [001] was aligned with the [110]-oriented sapphire substrate. These findings are promising for the future integration of blue-emitting ITO into optoelectronic devices.

NORIAKI HORIUCHI

ULTRAFAST OPTICS

Focusing through scattering media

A scattering medium such as biological tissue distorts the propagation of light pulses in both space and time, making tasks such as focusing and imaging problematic. Fortunately, careful manipulation of the light field's spatial phase prior to entering the medium can help mitigate such distortions and open new prospects for nonlinear microscopy.

Andrew M. Weiner

The scattering of waves propagating through inhomogeneous media is of interest across diverse areas of physics and engineering, including acoustics, radiofrequency wireless communication, optics and electron transport. In the optical domain, scattering-induced wavefront distortions limit focusing ability and degrade image quality. Adaptive optics can be used to address weak phase aberrations, such as those encountered in free-space optical communications and astronomical imaging through the atmosphere. However, compensating for the distortions that occur in strongly scattering media such as biological tissue is a more significant challenge.

In the case of diffusive light propagation, the output waveform is a noise-like (speckle) field, which generally shows no discernible resemblance to the input wavefront. However, by programming the spatial phase of the input field using a modern spatial light modulator, coherent light can be 'focused' through an opaque scattering medium to provide a 1,000-fold enhancement in intensity at the focus[1]. Such demonstrations, in which spatial degrees of freedom at the input are manipulated to generate spatially localized hot-spots in a continuous-wave laser speckle field at the output, offer exciting new prospects for microscopy and imaging in scattering media.

Writing in *Nature Photonics*, Katz *et al.* present experiments in which femtosecond pulses are manipulated to achieve focusing in space and time through scattering media[2]. The results show that spatial phase shaping prior to the input of a scattering medium yields temporal compression at the output. The researchers demonstrate and characterize the approach by performing two-photon fluorescence measurements after the pulses have passed through scattering media such as bone and brain tissue. They report strong and spatially localized enhancements to the two-photon yield by an estimated factor of 800. These results offer significant hope for potentially overcoming scattering in nonlinear biomedical microscopy — a field that already widely exploits two-photon excitation. The ability to program light for spatially localized pulse compression — and possibly pulse shaping — should enable new possibilities for coherent quantum control, laser machining and other nonlinear optical processes to be implemented in scattering environments.

From a scientific perspective, these experiments begin to address the fundamentally coupled nature of space, time and frequency for light propagation in the regime of strong multiple scattering[3]. For a single-frequency continuous-wave laser, the superposition of many randomly phased field contributions gives rise to a speckle intensity pattern[4], as shown at the output of the random medium in Fig. 1. If the input pulse is short, the medium also distorts the output in time, with a delay spread that corresponds to the length distribution of trajectories between the input and the output. Furthermore, at any specific spatial location, the output field acquires random substructure in both time (temporal speckle) and frequency (spectral speckle), which are related by the Fourier transform. Different substructure is therefore seen at different locations.

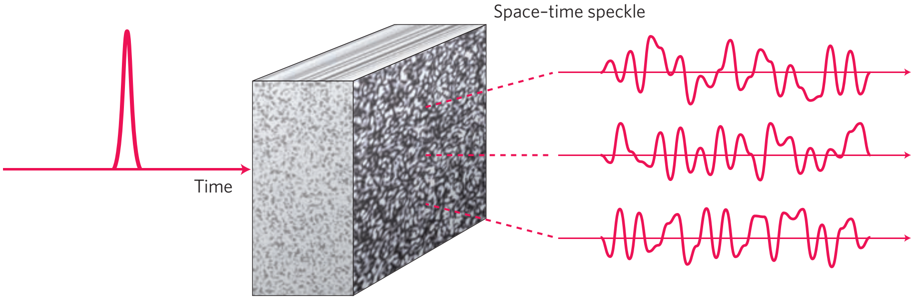


Figure 1 | Multiple scattering of a coherent input field in an inhomogeneous medium gives rise to a noise-like speckle field. For a short-pulse input, the output is stretched in time and exhibits a strong substructure due to random interference. The temporal speckle depends strongly on spatial position.

The experiments of Katz *et al.* can be understood as follows. As shown in Fig. 2, the field observed at any specific position at the output of the scattering medium is the superposition of the short-pulse responses from each of the individual spatial locations at the input. Each input-to-output pair has a pulse response with a random substructure similar to that of Fig. 1. The overall temporal response corresponding to the fully illuminated input surface is a random superposition of random temporal speckle patterns. By using a spatial light modulator to shift the optical phases of the contributing temporal speckle patterns, Katz *et al.* impose a correlation between these formerly random and uncorrelated contributions, causing them to selectively reinforce each other at the specified position in space over a time period determined by the inverse bandwidth of the input field.

There is an important distinction between the traditional notion of focusing light in the absence of aberrations and that achieved in experiments with strongly scattering media. An aberration-free lens concentrates light sharply at the focal plane, with very little energy found outside the localized focal spot. ‘Focusing’ light through scattering media does result in the formation of a hot spot with strong peak intensity (either in space[1] or in space and time[2]), but the hot spot is not background-free, unlike in traditional focusing. In fact, the hot spot may contain only a small fraction of the incident power, and the average spread of the power may change only minimally during the focusing process. Therefore, in order to observe such space–time focusing, one must either time-resolve the field or intensity for a selected speckle position in space or probe the intensity enhancement though a nonlinear interaction. In one recent study[5] that achieved space–time focusing in an apparatus similar to that of Katz *et al.*, researchers time-resolved the hot spot with the aid of an undistorted ultrashort reference pulse delivered directly from their mode-locked laser. Their measurement is an example of a technique known in the field of ultrafast optics as ‘electric field cross-correlation’. Katz *et al.* probe their space–time focusing through the nonlinear process of two-photon fluorescence. This brings the technique closer to the realm of applications because two-photon fluorescence is already widely studied throughout the field of two-photon microscopy.

Another approach for the compensation of multiple-scattering-induced distortions relies on the time-reversal technique, which has received significant attention for ultrasound[6] and radiofrequency[7] applications. Referring again to Fig. 1, imagine that each of the temporal waveforms, which correspond to each of the independent spatial samples in the output speckle field, are measured, flipped in time and then played back. According to time-reversal symmetry, the wave propagation now proceeds in reverse and the output fields recombine to form an undistorted replica of the original input. At frequencies of a few gigahertz and below, electronic oscilloscopes permit direct waveform measurement and electronic arbitrary waveform generators allow generation of the waveforms needed for time-reversal. Assuming a reasonable number of spatial samples, joint spatial and temporal control can provide very strong compensation, thereby sharply reducing the uncompensated background level. However, light is of a much higher frequency than a few gigahertz, and such experiments are therefore much more difficult to perform in the optical regime.

Researchers working with ultrawideband radiofrequency signals are also pursuing simpler time-reversal experiments that involve only a single spatial degree of freedom: a single transmitting antenna and a single receiving antenna. Such experiments are analogous to dispersion-compensation methods routinely employed in lightwave communications and ultrafast optics. In the wireless domain, certain classes of directional antennas have been optimized for broad-bandwidth use,

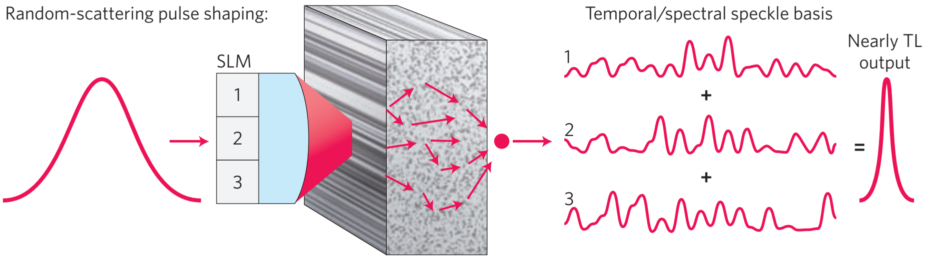


Figure 2 | The temporal speckle at any position within the medium is a random superposition of contributions from different points on the input surface. In the technique of Katz *et al.*, use of a spatial light modulator (SLM) causes these previously random and uncorrelated contributions to selectively reinforce each other, thereby achieving both spatial and temporal focusing. The output pulse may be restored nearly to the transform limit, and, if the input pulse is chirped (as shown here), compression may also be achieved. TL, transform-limited.

but these suffer from strong frequency-dependent delays that cause distortions in short-pulse propagation even without encountering multiple scattering. Applying time-reversal concepts, such waveforms can be predistorted (using photonic approaches that extend the available bandwidth of radiofrequency arbitrary waveform generation) so that they recompress when propagating through such antenna links, thereby overcoming antenna dispersion[8]. For the multiple scattering typical of indoor wireless propagation, time-reversal can be used to generate short peaks that optimize the signal-to-noise ratio for enhanced detection. Such peaking is also spatially selective in the sense that a wavelength scale displacement of the receiving antenna profoundly degrades the temporal peaking[9] — an effect that may prove useful for enhancing the security of wireless communications. This scenario, which involves manipulating only the temporal degrees of freedom at the input, poses an interesting parallel to the optical experiments[2,5] of Katz *et al.* and Aulbach *et al.*, which involve manipulating only the spatial degrees of freedom at the input. Both experiments result in spatially selective peaking in the time domain. Further fascinating possibilities arise when strong scattering occurs at the subwavelength scale. In this regime, space–time focusing has been achieved with subwavelength spatial selectivity, both in radiofrequency propagation[7] and in the femtosecond optical excitation of plasmonic nanoantennas[10].

It is clear that the strong mixing of spatial and temporal degrees of freedom through multiple scattering can lead not only to new phenomena in a wide range of physical systems, but also to new opportunities for counteracting or exploiting these phenomena. The experiments of Katz *et al.*, which demonstrate space–time focusing to enhance a two-photon nonlinear process, dramatically illustrate such opportunities and point the way towards using them for enhancing microscopy in turbid samples. ❐

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References

1. Vellekoop, I. M. & Mosk, A. P. *Opt. Lett.* **32,** 2309–2311 (2007).
2. Katz, O., Small, E., Bromberg, Y. & Silberberg, Y. *Nature Photon.* **5,** 372–377 (2011).
3. Webster, M. A., Gerke, T. D., Weiner, A. M. & Webb, K. J. *Opt. Lett.* **29,** 1491–1493 (2004).
4. Goodman, J. W. *Speckle Phenomena in Optics* (Roberts & Co., 2007).
5. Aulbach, J., Gjonaj, B., Johnson, P. M., Mosk, A. P. & Lagendijk, A. *Phys. Rev. Lett.* **106,** 103901 (2011).
6. Fink, M. *Phys. Today* **50,** 34–40 (March 1997).
7. Lerosey, G., de Rosny, J., Tourin, A. & Fink, M. *Science* **315,** 1120–1122 (2007).
8. McKinney, J. D., Peroulis, D. & Weiner, A. M. *IEEE T. Microw. Theory* **56,** 710–718 (2008).
9. El-Sallabi, H., Kyritsi, P., Paulraj, A. & Papanicolaou, G. *IEEE T. Instrum. Meas.* **59,** 1537–1543 (2010).
10. Aeschlimann, M. *et al. Nature* **446,** 301–304 (2007).

Correction

In the News & Views 'Avoiding indium' (*Nature Photon.* **5,** 201–202; 2011), credit for Figure 2 was incorrectly given to Linköping University. The figure was originally published in ref. 22 of the News & Views (Manceau, M., Angmo, D., Jørgensen, M. & Krebs, F. C. *Org. Electron.* **12,** 566–574; 2011) and credit should therefore have been given to Elsevier and Frederik Krebs Laboratory.

This error has been corrected in the HTML and PDF versions.