light by interference effects, giving rise to the phenomenon of light localization even in the absence of disorder. The anomalous wave propagation in 3D quasicrystalline structures is not well characterized, and it is a problem that outsmarts current computers. The method of Ledermann and colleagues may provide high-quality samples for such a study.

The ultimate route to creating photonic-crystal components may well be an inverse approach, in the sense that the functionality is pre-specified, and the structure is then found by some kind of mathematical inverse algorithm. In this inverse-type method, the optimal structure could be very complex and DLW fabrication techniques might hold the answer to making such structures as long as they are self-supporting.

One of the most exciting recent developments in optical physics is the demonstration that it is possible to obtain control over the speed of a pulse of light as it travels through transparent photonic materials. Unfortunately, manipulating the speed of light pulses can severely distort their shape, which limits their uses.

Now, in a recent publication, Mok et al. demonstrate that self-replicating nonlinear optical-pulse propagation can get around this problem and produce a controllable pulse velocity while simultaneously minimizing pulse distortion.

The development is interesting as it provides another method to delay light pulses without significantly changing their shape. This is particularly relevant in the field of optical communications where it is important that manipulated light pulses representing digital data bits do not become smeared or distorted, which would lead to transmission errors.

These recent results are the latest in a line of achievements that span several years of research into slow light. Early research in the late 1990s and early 2000s on such slow-light behaviour studied pulse propagation through a gas of atoms pumped by an intense optical field. Truly amazing results were obtained: the pulse speed — known as the group velocity — could be as low as a few tens of metres per second in comparison with the vacuum speed of light, c = 3 × 10^8 m s⁻¹ (ref. 2). More recent work has demonstrated that this slow-light effect can be obtained in standard off-the-shelf optical-telecommunication fibres and that, in principle, there is no fundamental limitation to the pulse delays that can be obtained. The real challenge is identifying slow-light schemes that are practical to implement and do not induce pulse distortion.

To understand this challenge, let’s review briefly why a pulse slows down as it propagates through an optical material. A pulse of light is effectively composed of an infinite number of perfect sinusoidal electromagnetic waves, each with a different frequency, as shown in Fig. 1a. The pulse peak corresponds to the space-time point of constructive interference of these component waves, with destructive interference occurring in the pulse wings. When a pulse propagates through vacuum, each of the component waves travels at c and hence the point of constructive interference (the pulse peak) also travels at c as shown in Fig. 1b.

The situation is somewhat more complicated when the pulse propagates through a material such as an optical fibre. Optical materials are characterized by an index of refraction and a coefficient of absorption that depends on the frequency of the light. In this situation, each of the component waves making up the pulse travels at a different speed and each frequency is attenuated by a different amount. The net result is that the pulse is distorted as it travels through the material in comparison with how it would travel over the same path in vacuum as shown in Fig. 1c.

However, for a material that is attenuation-free and has a refractive index that is a linearly increasing function of frequency, the pulse ‘distortion’ is merely a delay of the pulse. Nothing else about the pulse, such as the shape of the pulse envelope, changes. This is the ideal slow-light medium.

Unfortunately, nature is not so kind. There exists no such material. In fact, such a material would violate a fundamental physical principle known as causality, where an event is always preceded by a cause rather than the other way around. So the question is how well can we do with physically realizable materials?

Much of the recent slow-light research on room-temperature optical waveguides has focused on using the variation in the refractive index of the material induced by a strong laser beam that pumps the material. Processes such as stimulated Brillouin scattering and stimulated Raman scattering create an amplifying resonance in the material, which is characterized by a frequency-dependent change in the index of refraction giving rise to slow light.

Such a resonance approximates the ideal slow-light medium only over a small finite spectral bandwidth. As a result, these schemes are only compatible with pulses within a small frequency window. If the pulses are too short (broad bandwidth) or at slightly
the wrong central wavelength, then further pulse distortion, such as pulse broadening, arises, which is devastating for applications in telecommunications.

Several groups are using dispersion-compensation methods to make the slow-light medium closer to the ideal, where an increase by a factor of two or more in the pulse delay has been achieved while maintaining acceptably low pulse distortion\(^\text{15}\).

Other groups have taken very different approaches and have also obtained large delays with low distortion\(^\text{10}\).

The work of Mok et al.\(^\text{1}\) falls into the second category. They have studied the propagation of a 680-ps-long pulse that is so intense it induces a change in the material's refractive index. The change in refractive index is proportional to the instantaneous pulse intensity.

The experiments exploit a specially designed fibre Bragg grating — a tiny periodic modulation of the (linear) refractive index along the length of the fibre. For low pulse intensities, this periodic modulation gives rise to Bragg reflection of light when the centre wavelength of the pulse (1.06 μm) matches the spatial scale of the periodic modulation.

Essentially, the fibre acts like a highly reflective thin-film dielectric mirror found in a typical optics lab, but its length is 10 cm rather than just a few thin layers. Near the edge of the reflecting band, the change in the linear refractive index of the structure is large, giving rise to a large slow-light effect but with large distortion.

Pulse distortion can be avoided by operating in the nonlinear optical regime. When the nonlinear change in refractive index is high enough, the resonance of the Bragg reflector shifts so that the waveguide switches to a high transmission state. In addition, the dispersion associated with the Bragg reflector is just compensated by the time-dependent nonlinear change in refractive index, resulting in a pulse that propagates without change — known as an optical soliton\(^\text{11}\).

Using this method, Mok et al. have obtained a slow-light delay time that is about two and a half pulse widths and can be adjusted by changing the intensity of the input pulse. The fact that they have been able to delay a pulse by more than the width of the pulse is important because such a slow-light delay line can already find applications in the resynchronizing of a stream of optical data (pulses) with the telecommunication-system master clock.

Of course, there are still many challenges ahead to integrate this method into a telecommunication system. One issue is that the necessary pulse intensity to observe soliton formation is very high — of the order of a kilowatt, which is about 10,000 to 100,000 times larger than the typical pulse intensities in a telecommunication system. This problem could be solved using recently available nonlinear materials that have a larger nonlinear effect, as discussed by Mok.

Other issues include the relatively low transmission of the system and the sensitivity of the delay time to the input intensity. But of greater concern is that the authors have only studied a single pulse propagating through the nonlinear Bragg reflector. A telecommunication system necessarily involves several pulses and, once these pulses enter the Bragg reflector and form solitons, pulse-to-pulse nonlinear interactions might deleteriously affect the system performance. My best guess is that these interactions will be important, but may not be a show-stopper.

So what good is all of this? Ultimately Mok et al.\(^\text{1}\) have added a device to the ‘slow-light toolbox’ that should allow optical-telecommunication engineers to increase the efficiency and throughput of the information highway.

References