circular layers of air voids embedded in soft glass. Their manufacturing technique allows fibres to be drawn to several hundreds of metres in length. The fibres can transmit light within a bandwidth of more than 100 nm, centred at around 750 nm, in the red region of the spectrum. Not surprisingly, the attenuation is elevated compared with the best performing PCFs, yet it remains at an acceptable level of 6 dB m^{-1}. Of course the losses could probably be lowered in the future with improved design and a better quality manufacturing process. Furthermore, higher-order modes experience much larger propagation losses than the fundamental mode, which renders the fibre practically single-mode. Most importantly, the chirped PCF exhibits low dispersion and reduced wavelength dependence across the entire transmission band. This is of interest for ultrashort pulse delivery, where the large dispersion typically observed in a conventional PCF leads to strong temporal spreading and distortion.

The potential damage caused by high-intensity light within the confinement medium poses potential problems. However, the main challenge associated with guiding ultrashort pulses containing only a few cycles of the carrier oscillation frequency is their tendency to spread very rapidly with propagation distance, owing to the dispersive nature of the medium. It is clear that photonic-crystal fibres offer the possibility of keeping light tightly confined in air or vacuum over long distances with low
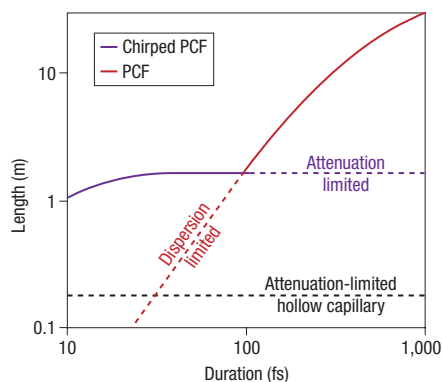

Figure 2 Maximum usable fibre length versus pulse duration for the 53-µm-core chirped PCF reported by Skibina *et al.* and a conventional PCF. The maximum length is determined using the arbitrary criterion that 10% of the initial pulse energy remains located within the initial pulse profile after propagation.

attenuation. But they fail when it comes to delivering ultrashort pulses because of their strongly dispersive characteristics. Hollow-capillary waveguides consisting of an empty glass cylinder are an alternative commonly used in high-field experiments, where limiting dispersive effects that reduce nonlinear interactions is crucial. However, although hollow capillaries offer reduced dispersion, they are intrinsically very lossy for tight beam confinement, making them unsuitable for carrying short laser pulses over distances exceeding tens of centimetres. And this is where the chirped PCF has the advantage: it provides a route towards

combining low loss and low dispersion, which is ideal for ultrashort pulse delivery. To prove the effectiveness of their concept, the authors demonstrate the propagation of 13-fs pulses in a 1-m-long chirped PCF, which is impressively only broadened by a factor of two. Comparatively, a traditional PCF stretches the pulse by more than a hundred times its original duration.

Biology and medicine could benefit from the chirped photonic-crystal fibre capabilities when delivery of pulses with a duration of less than 100 fs is needed (Fig. 2). Another playground that could be a clear winner is extreme nonlinear optics, where very large intensities are required to access phenomena such as supercontinuum generation, high-harmonic generation, carrier shocking and many more, as high and strongly varying dispersions are severely limiting factors. Also, the prospect of infiltrating a gas into the hollow core for strong nonlinear interaction studies is enticing.

The chirped photonic-crystal fibre is certainly not perfect yet: an effort is definitely needed to decrease attenuation. But the concept introduced here is truly worth pushing further and will hopefully stimulate further developments in the performance of chirped PCFs with, perhaps, an extension to a more complex design or operation in different regions of the electromagnetic spectrum.

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PHOTOVOLTAICS

The two sides of solar energy

A bifacial dye-sensitized solar cell that can efficiently generate electricity when illuminated from either side may help bring down the cost of solar energy production.

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Following extensive research in semiconductor photoelectro-chemistry in the 1970s, the dye-sensitized solar cell (DSC) was invented in the early 1990s (ref. 1). Ever since, it has been a topic of intense research

and chemists have developed a large family of dyes with the core function of converting the energy of an incident photon into a molecular excitation, which is subsequently transformed into separate electron and hole charge carriers. The dye is typically combined with a nanoporous TiO$_2$ structure that functions as electron collector and is surrounded by an ionic conductor, often in the form of a liquid electrolyte. The entire

structure is sandwiched between two layers of glass. The result is a solar cell that can generate electricity without the need for crystalline silicon or any other expensive semiconductors.

With the increase in oil prices and growing awareness of the need for major renewable energy sources, the photovoltaic market is booming. There are expectations that the DSC, a device that can be fabricated at potentially

very low cost, will become a significant player in future large-scale solar energy schemes. Several companies already have serious investments and ambitions in the area. For example, Australia-based Dyesol, a seller of DSC components, has rapidly expanded. Sony has announced the achievement of DSC modules with 7% energy conversion efficiency, and G24 Innovations in Wales has established major production facilities for flexible DSCs.

A key issue with all designs of DSC is the optimization of their conversion efficiency — the fraction of light intensity that is converted into electrical power. Among the many researchers involved in DSCs, Swiss scientist Michael Grätzel figures prominently, for both his role in the inception of the field and major device developments afterwards, such as the solid DSC (ref. 2). On page 693 of this issue[3], Seigo Ito in Japan and researchers from Grätzel's lab report an optimized stable configuration of DSC that has a similar conversion efficiency when illuminated from either its front or rear side.

The golden rules in solar-cell design are simple: do not lose light, and absorb all the photons that you can. But there is a trade-off between obeying these rules and effective handling of the photo-generated electronic charges (electrons and holes). For example, the thickness of a cell cannot be extended indefinitely to improve light absorption, as at some point the electron and hole transport pathways become too large and the cell performance decreases owing to internal electrical resistance. It is also mandatory to extract the photogenerated electrons out of the TiO_2 network within their lifetime, before they are internally lost by recombination with holes.

Optimized light management is therefore about obtaining acceptable values for the parameters ruling the steady-state operation of the solar cell — in particular, the voltage at open circuit, V_{oc}, and the generated photocurrent density, J_{sc}. The parameter V_{oc} is a measure of the accumulation of electrons and holes when no current flows, and is effectively governed by recombination[4]. The parameter J_{sc} is the electrical current density when the device operates with an external short circuit under an illumination equivalent to 1 Sun (1,000 W m^{-2}, AM 1.5G standard conditions)[5].

Various approaches for optically optimizing DSC performance have been reported. These include the use of an additional layer of relatively large
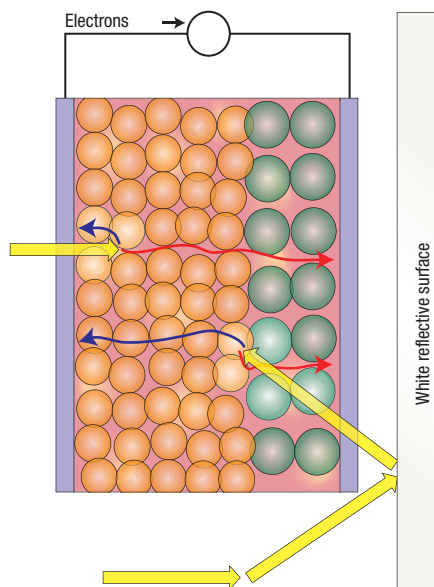

Figure 1 A schematic of a dye-sensitized solar cell operating in bifacial mode in front of a white reflector. The small yellow spheres are dyed TiO_2 nanoparticles that form an interconnected network and are connected to a transparent front contact (electron collector, shown in purple). The larger green spheres indicate transparent SiO_2 particles that separate the TiO_2 layer from the transparent back contact (hole collector, shown in purple). The black and red arrows indicate the pathways of a photogenerated electron and hole, respectively, in the TiO_2 region. Two example pathways are shown, that is, the uppermost for front-side illumination and generation near the front contact, and the lower for rear illumination near the TiO_2–SiO_2 boundary. Yellow arrows indicate photons, and the pink region indicates the ionic electrolyte.

(400 nm) TiO_2 nanoparticles, which act as an internal scattering reflector for the layer of 20-nm-sized TiO_2 particles that perform the photovoltaic conversion. This approach can improve the photocurrent by more than 10% (ref. 6). A more recent idea is the construction of photovoltaic Bragg mirrors by spatial modulation of the TiO_2 nanoparticle size[7].

The bifacial cell suggested by Ito et al.[3] in this issue collects sunlight from both sides of the solar cell. An example of how this may be deployed in practice, already tested with inorganic bifacial cells[8], is shown in Fig. 1. The scheme relies on placing spaced DSCs in front of a white or semitransparent reflector, to collect both light from the front and that returning from the reflector. Although DSCs are routinely encapsulated between transparent glass (covered with a thin conducting layer of fluor-doped tin oxide, FTO, for charge transport out of the cell) on both sides,

effective bifacial operation requires fine tuning of a number of aspects.

The main issue is transparency of the rear side of the DSC. In a DSC the liquid electrolyte contains I$^-$ ions that transform into I$_3^-$ by redox reaction when they accept holes from (or donate electrons to) the oxidized dye. But robust DSCs, able to withstand outdoor operation over prolonged periods of time, use viscous media called ionic liquids, to support the redox carrier that electrically connects the dye with the back electrode.

The combination of ionic liquid with the redox ions provides good and stable photovoltaic performance but poor transparency, which is one of the main issues for the development of efficient bifacial DSCs. Ito et al. solve this problem by using SiO_2 particles on the back side of the cell and an optimized thickness for the TiO_2 layer. This strategy exploits the knowledge that insulating nanoparticle fillers, such as Al_2O_3, increase the ionic conductivity of salts or polymers used in lithium batteries[9]. The SiO_2 particles used by Ito et al. effectively channel the light through the viscous electrolyte. This is shown to be more effective than placing the back contact directly on top of the dyed TiO_2 film, which produces an internal current in the unwanted direction. The gain is clear in the improvement of J_{sc} demonstrated in the paper.

Another important and related factor is the optimization of the photoactive TiO_2 layer thickness. In the bifacial cell the layer must receive light from both sides. Carrier generation close to the front contact implies a short collection path for electrons and very long (about 10 μm) for the redox ions, whereas the opposite case occurs for photogeneration from backside incident photons, as indicated in the diagram of Fig. 1. Ito et al. analyse the balance between light absorption and transport of both electrons and ions in relation to thickness.

The development presented by Ito et al. is timely, as DSC panels scale up from the small, research size of about 0.5 cm^2, to the very large area that is required for routine electricity production.

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