

thicknesses of several centimetres, such as in mammography? The method could be easily combined with time-gating techniques^{6,7} to select the less scattered light. Yaqoob *et al.* propose using their method to improve the depth penetration in photoacoustic tomography⁸, where pulsed light excites an ultrasound wave. They also suggest enhancing light delivery to photodynamic therapy in a manner analogous to the use of time reversal to deliver high-frequency ultrasound dosages for the removal of kidney stones⁹. If the tissues of interest have fixed, strongly

scattering particles, a weak wave diffused by these particles can be phase-conjugated and amplified to focus strong illumination on the particles and to spare tissues where particles are absent, as shown in Fig. 1.

The experiments of Yaqoob and colleagues are impressive because they could offer a possible means of removing some of the present limits in medical imaging and therapy today. In the future, the method should enable imaging through thicknesses much greater than that of 0.7 mm demonstrated in the experiment by Yaqoob and colleagues, and

when combined with real-time imaging and more appropriate wavelengths it could start to look very promising for applications.

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SOLAR CELLS

Slicing and dicing photons

Solar cells take advantage of our most abundant source of energy, the Sun. A technique that improves the conversion of photons to electrons could potentially lead to a dramatic improvement in device efficiency.

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Optimizing the conversion of photons to electrical energy, with minimal thermal loss, provides a fundamental scientific challenge that promises significant advances for solar-energy technology. The efficiency of conventional single-bandgap photovoltaic cells is limited by the heat generated as the photogenerated electrons and holes scatter from phonons and relax to a lower energy state (Fig. 1). For example, a conventional silicon solar cell operating at the thermodynamic maximum efficiency under AM1.5G simulated solar illumination (equivalent to the Sun) converts about 47% of the incident solar power to heat. On page 105 of this issue¹, Dolf Timmerman and a Dutch research team in collaboration with scientists from Portugal and Russia report a route to circumvent such losses.

The idea underpinning the team's approach is the ultrafast division of the energy from an absorbed photon into two or more spatially separated excited states (Fig. 1c). The process, termed space-separated quantum cutting (SSQC), suggests a physical process for very rapid energy transfer between neighbouring chromophores. Space-separated quantum cutting may provide a new route for

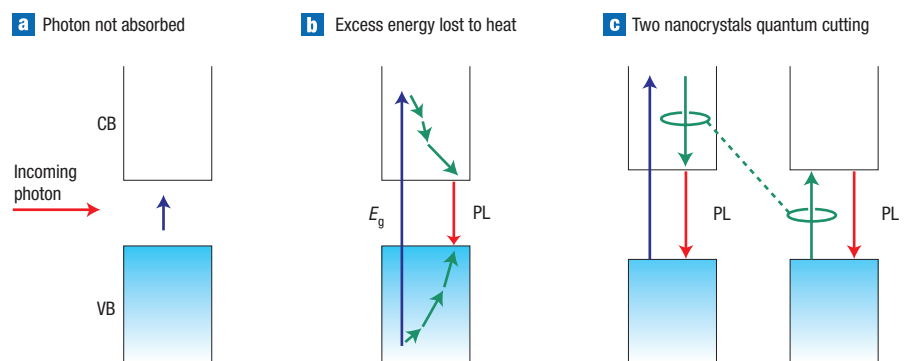


Figure 1 The absorption of a photon in a silicon nanocrystal excites an electron from the valence band (VB) to the conduction band (CB). **a**, Photons with energy less than the bandgap, E_g , are not absorbed. **b**, The excess energy from photons with more energy than the bandgap is lost as heat. **c**, The quantum-cutting process transfers some of this extra energy to a second nanocrystal, allowing it to be used to generate another photon by photoluminescence (PL).

improving the efficiency with which photovoltaic cells convert higher-energy photons into electricity.

Timmerman and co-workers demonstrate SSQC within SiO_2 matrices containing both silicon nanocrystals (NCs) and erbium ions (Er^{3+}), and also within SiO_2 matrices containing only silicon NCs (ref. 1). The efficient transfer of energy from photoexcited silicon NCs to Er^{3+} ions has been previously documented through photoluminescence observations^{2,3}. Now, Timmerman *et al.* describe a process

whereby a silicon NC absorbs a photon, and rapidly transfers a fraction of that photon's energy to generate a proximal but distinct excited state within either an erbium ion or another silicon NC. During the initial energy-transfer process, the original silicon NC relaxes from a highly excited state towards the lowest-energy excited state. The net result is two photons emitted for each photon absorbed.

The SSQC process bears some resemblance to the process of multiple exciton generation (MEG), which occurs

efficiently in colloidal semiconductor NCs and was first reported experimentally using PbSe NCs in 2004 (ref. 4). In the MEG process, absorption by an NC of a single photon of sufficient energy generates two or more excitons within the NC. Interestingly, colloiddally suspended silicon NCs have also been shown to exhibit MEG (ref. 5). However, efficient separation of electrons from holes for multiple excitons within a single NC remains a challenging scientific and technical barrier, with no conclusive reports so far of multiple excitons contributing more than one electron to the photocurrent in a working device. Although the materials system used by Timmerman *et al.* does not provide an obvious simple route to photocurrent collection, the distinct nature of the resulting excited states may provide another avenue to improving the efficiency with which high-energy photons are used in solar cells. A notable finding in the current work concerns the energy threshold for the process: whereas the energy-conservation threshold for MEG is twice the NC bandgap, $E_{g(\text{Si NC})} \approx 1.36$ eV, the energy threshold for SSQC using 3-nm diameter silicon NCs together with Er^{3+} ions is given by the sum of the NC bandgap and the erbium excitation energy, $E_{\text{Er}^{3+}} \approx 0.81$ eV, and is therefore lower.

In semiconductors, photogenerated charge carriers with excess energy above the band edge relax on the subpicosecond

timescale through phonon scattering. Thus, the successful generation of multiple excited states (either by MEG or by SSQC) must necessarily compete with the phonon scattering rate. Carrier relaxation dynamics have not been reported for silicon NCs, perhaps owing to measurement complications associated with the indirect bandgap in the electronic structure of silicon. However, in the characterization of cooling dynamics for several other types of NCs such as InP, CdSe and PbSe, the cooling times fall generally in the subpicosecond range. It is noted by Timmerman *et al.* that cooling may be slower in indirect-bandgap materials such as silicon; nonetheless, it is likely that the SSQC process occurs over very short timescales, perhaps on the order of 100 fs or less. One possible mechanism relates to the extended wavefunction associated with high-energy excitation: the authors propose that the ultrafast energy-transfer process results from an inter-chromophore impact-ionization interaction between the energetic exciton in the silicon NC and a ground-state electron in the neighbouring chromophore. This scenario requires that the chromophores reside very near to one another, and this is indeed the case for the measurements reported thus far (about 50% of the NCs have at least one neighbouring NC within a distance of 1 nm). Interestingly, efficient MEG has been characterized for films consisting of closely spaced and electronically coupled PbSe NCs (ref. 6);

this nanomaterial system may very well benefit from both MEG as well as SSQC, and may indeed eventually lead to a coherent understanding of whether the two processes share common physical origins.

The evident demand for inexpensive carbon-free energy continues to drive research and development on novel approaches to generate electricity and fuels from sunlight. As silicon accounts for more than 90% of global photovoltaic-cell production, this report of space-separated quantum cutting in silicon NC systems illuminates an important possible route towards the goal of inexpensive and highly efficient solar-energy conversion. As remains the case with the MEG process, significant questions must be answered regarding the mechanism, dynamics and absolute efficiency of SSQC. The ultimate impact of SSQC to solar energy conversion depends on its ability to survive the tests of careful scrutiny, the absolute efficiency with which it occurs and our ability to efficiently exploit this nanoscale process in macroscopic devices.

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LIGHT AND MATTER INTERACTIONS

Going with the grain

Non-reciprocal optical phenomena — effects that depend on the direction of light propagation — are rare. Researchers have now observed non-reciprocal material modification when moving a beam of ultrashort light pulses through a lithium niobate crystal.

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It is well known that a tightly focused femtosecond laser pulse can heat up a microscopic volume inside a transparent sample, such as glass. For more than ten years, researchers have been studying this phenomenon and using it to micromachine miniature devices and fabricate three-dimensional waveguides. However, until the work by Weijia Yang and

colleagues reported on page 99 of this issue¹, little research has focused on whether the direction of the light beam's propagation can influence the effects induced in the material.

Now, Yang and colleagues have shown that material modifications induced by femtosecond laser pulses can be distinctly different when a laser beam propagates in opposite directions. Their tests were performed with a LiNbO_3 crystal — an anisotropic crystal widely used in nonlinear photonics applications¹.

Phenomena that are non-reciprocal are uncommon in optics. In Faraday rotation,

the direction in which the polarization of linearly polarized light rotates depends on whether the light propagates parallel or antiparallel to an applied magnetic field. This effect is often used to produce optical isolators that act as one-way valves for light. No previous studies, however, have demonstrated non-reciprocal optically induced modification of material properties.

In recent years, femtosecond laser irradiation has provided a new means of locally altering the optical properties of transparent materials. When a femtosecond laser pulse is tightly focused

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