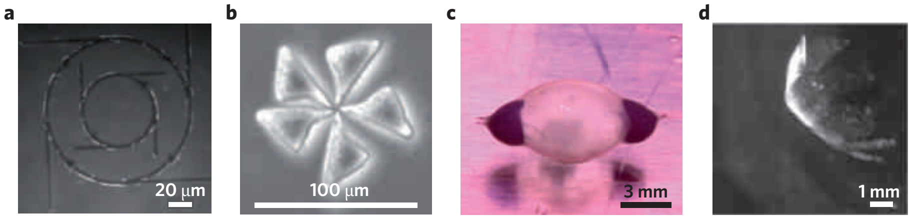

Figure 2 | Biohybrid devices propelled by biological motors, bacteria or cardiomyocytes. **a**, The biological motor kinesin propels molecular shuttles in microfabricated channels. **b**, Flagellated bacteria rotate a microfabricated object. **c**, Cardiomyocytes pump fluid through a microfabricated polymer. **d**, Cardiomyocytes propel a polymeric medusoid body. Figure reproduced with permission from: **a**, ref. 9, © 2007 Springer; **b**, ref. 7, © 2004 Elsevier; **c**, ref. 6, © 2006 RSC; **d**, ref. 8, © 2012 NPG.

is similar to the swimming efficiency of living ephyrae.

Using this close interplay of characterization of a biological propulsion system complemented by a computer simulation-supported design, Parker and colleagues illustrate how to assemble prototypes of functionally equivalent substitutes from synthetic and tissue-engineered materials. They have successfully mimicked one stereotypical mode of forward propulsion. The medusoids are, however, clearly simplified systems compared with their jellyfish cousins. Multiple pacemaker centres allow the jellyfish to fine-tune local contractions, and thus to control turning and manoeuvring. More complex systems that better mimic the presence of multiple and well-coordinated pacemaker centres may offer such features in the future. This approach of emulating nature could be extended to mimic the movement of other biological organisms.

The contractile properties of cardiomyocytes can be exploited for functions other than propulsion: tissue engineers are keen to learn how cardiomyocytes cultured within microstructured polymers can be used to build biohybrid pumps that mimic elemental features of a simplified heart (Fig. 2c)[6]. Scientists have also shown how engineered objects can be moved within microshaped, biohybrid devices powered by either molecular biological motors[5,9] or by the rotating flagella of swimming bacteria[7] (Fig. 2). Thus, learning how to imitate various facets of living creatures should open the door to a variety of soft robotic systems for medical or technical use. This could include soft robotics for operation in aqueous environments[10], for example synthetic mimics of an octopus with an ability to squeeze its body through tiny holes, or a fish capable of swimming over large distances.

The challenge ahead is to dissect the operation principles of complex biological machineries into the elemental components, and determine how they cooperate at different length scales, and then to ask how such a complex design can be re-engineered with available technologies. In most cases, this may not require the exact reproduction of biological systems, but the fusion of biological and technological construction principles. There is, therefore, plenty of room for new engineering designs inspired by the diverse propulsion modes of living creatures. ❐

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PHOTONICS

Upconversion goes broadband

Upconversion nanoparticles that convert low-energy light into high-energy light hold promise for boosting solar-cell efficiency and enabling highly sensitive biological assays. But their spectral conversion under broadband excitation has been challenging, until now.

Xiaoji Xie and Xiaogang Liu

Photon upconversion is a process that converts low-energy light, usually at near-infrared or infrared wavelengths, to higher-energy photons. Such processes have implications for a variety of technologies, including photovoltaics and biological imaging[1–3]. Upconversion nanoparticles can be integrated into silicon-based solar-cell devices as spectral converters that effectively convert incident light with energies smaller than the semiconductor bandgap, which is not absorbed, into light having sufficient energy to be absorbed[4]. These upconversion nanoparticles could enable biological imaging at substantial depths with enhanced contrast and high spatial resolution because of the absence of natural light-emission in biological samples under infrared excitation[5]. However, further progress in utilizing upconversion processes has been constrained by low conversion efficiencies, largely due to the extremely weak and narrowband near-infrared absorption of the nanoparticles used[6]. Writing in *Nature Photonics*, Wenqiang Zou and colleagues[7] now show that it is possible to dramatically enhance the upconversion luminescence of nanoparticles by using organic dye molecules as sensitizers that enhance the absorption of infrared light by the nanoparticles.

For an upconversion process to proceed, trivalent lanthanide ions such as Er^{3+}, Tm^{3+} and Ho^{3+} are typically used as activator ions. These ions feature ladder-like arranged energy levels where consecutive absorption of low-energy light pushes electrons up to higher energies[8]. To enhance upconversion luminescence efficiency, Yb^{3+} ions with a sufficient absorption cross-section in the near-infrared region are co-doped as sensitizer ions. When illuminated with a near-infrared diode laser, the Yb^{3+} sensitizer ion can absorb pump photons and then transfer the accumulated excitation energy to an activator ion such as Er^{3+} that emits this energy as high-energy, upconverted luminescence. However, for this process to work efficiently, the laser output wavelength and the absorption band of the sensitizer ion must be closely matched. Efficient pumping is realized only at wavelengths near 975 nm, and the pump linewidth must be small due to the narrow absorption bandwidth of the sensitizer ion at 975 nm.

Zou and colleagues now provide a much-needed solution that allows for more flexibility across a broad range of wavelengths. They show that the use of a suitably designed cyanine dye molecule enables a broadband excitation of sodium yttrium fluoride ($NaYF_4$) nanoparticles co-doped with Yb^{3+} sensitizers and Er^{3+} activator ions. In their study, the dye used, carboxylic acid-modified cyanine dye, which binds to the surface of the nanoparticles, acts as an antenna to trap photons with energies across a much broader wavelength range (740–850 nm) and then transfers this energy to the Yb^{3+} ions embedded in the host lattice (Fig. 1). Subsequently, the Er^{3+} ions accept the energy from the excited Yb^{3+} ions, resulting in a distinctive upconverted emission from the Er^{3+} ions. Strikingly, the integrated spectral response of the dye-sensitized nanoparticles in the wavelength range 720–1,000 nm is enhanced by 3,300 times compared with its normal level in control samples without dye modification.

Why does this work so well? According to the classical Förster theory[9] of energy transfer, the energy donor and acceptor must be placed in close proximity, typically less than 10 nm. If the separation between the donor and the acceptor is beyond the Förster critical distance of 2 to 6 nm, the energy transfer tends to be less efficient. Indeed, this was the case in studies that simply mixed nanoparticles and dye molecules. An essential requirement needed to generate efficient upconversion is therefore to control the density of the dye molecules on the surface of the nanoparticles. To avoid luminescence quenching, an estimated surface coverage of about 70 dye molecules with an intermolecular distance of ~3.4 nm on each nanoparticle is needed for it to perform optimally.

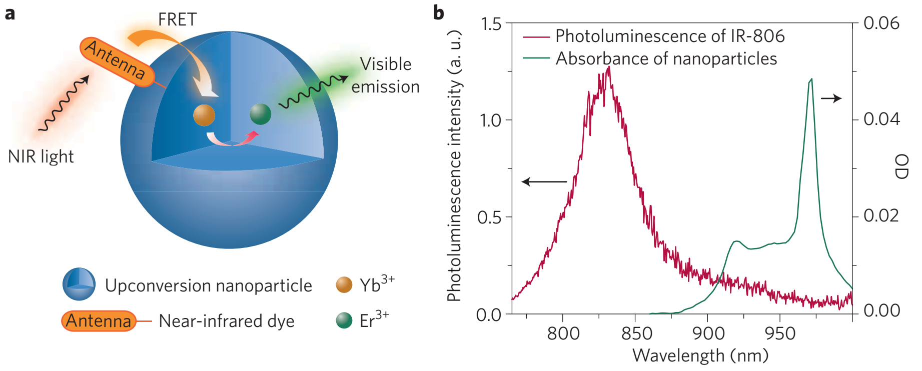

Figure 1 | The dye-sensitized upconversion. **a**, Schematic of the dye-sensitized nanoparticle. Near-infrared (NIR) light is absorbed and the energy transmitted to the Yb^{3+} ion through a so-called Förster resonance energy transfer (FRET). The Er^{3+} ion then accepts the energy from the excited Yb^{3+} ion, giving rise to upconverted Er emission. **b**, Emission (red) and absorption (green) spectra of the cyanine dye (IR-806) and the $NaYF_4$-Yb–Er nanoparticles. The emitted light has a higher energy than the light absorbed by the nanoparticles[7]. OD, optical density.

The discovery of dye-sensitized upconversion is encouraging because it provides for the first time the upconverted emission from lanthanide activators under a broadband, low-power excitation. A broader wavelength tuning range is further expected through rational design of the dye–activator combination, provided that the conditions for efficient Förster resonance energy transfer can be met. For example, this discovery sheds fresh light on finding new ways of breaking the classical Shockley–Queisser efficiency limit for single-gap solar cells[10]. Given the small particle size and solution-processable property of the nanoparticles, it is convenient to apply these upconverters to existing solar cells with few changes for enhanced conversion efficiency. The new cell design can prevent the transmission loss by absorbing a larger fraction of two near-infrared photons that otherwise would not be absorbed by the solar cell to produce one higher-energy photon that does get absorbed.

Another exciting feature of this discovery is that the key capability of dye-sensitized upconversion nanoparticles should lead to important and immediate applications in biological imaging. Conventionally used 980 nm laser sources for biological imaging often cause strong water absorption and sample overheating. This could degrade image resolution, limit the imaging penetration depth of light, and possibly result in substantial cell and tissue damage. In contrast, the use of an 800 nm excitation source for the nanoparticles is likely to significantly improve the signal strength at a deep sample depth, because water absorption at 800 nm is much less efficient than at 980 nm. The 800 nm laser also minimizes the sample overheating problem. However, a looming challenge remains to reconstruct high-quality upcoversion nanoparticles with improved electronic and optical properties that can outperform conventional fluorescent bioprobes — and that will certainly take considerable efforts. ❐

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