Nature Reviews Materials | Published online 19 Apr 2016; doi:10.1038/natrevmats.2016.27

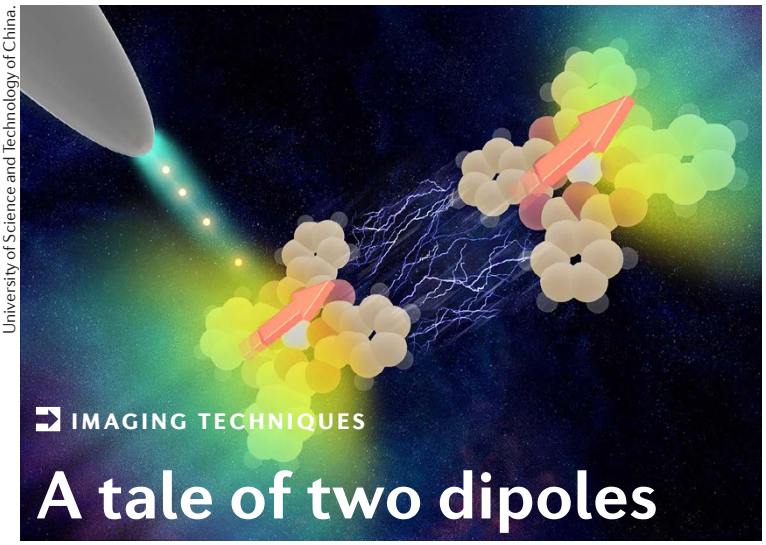

Image courtesy of G. Wang and D. Sun, University of Science and Technology of China.

> This technique [...] allows us to map the spatial distribution of the emitted light intensity [...] with sub-nanometer resolution superior to all-optical approaches

Many energy transfer and optical processes in both natural and artificial systems depend on dipolar interactions between molecules, which are very difficult to observe. Now, real-space imaging of these interactions between chromophore molecules has been reported by Zhen-Chao Dong and colleagues, from the University of Science and Technology of China (USTC), using a technique based on scanning tunnelling microscopy (STM).

Chromophores — best known for their role in photosynthesis — are molecules that adsorb visible light with a certain wavelength and re-emit it with a different wavelength. Energy transfer between these molecules, which allows the transport of the energy derived from sunlight absorption to reaction centres, is strongly influenced by the interactions between the electric dipoles of the molecules. Up to now, efforts to directly study these interactions in real space have been hindered by the diffraction limit imposed by classical optics. Dong and colleagues circumvented this obstacle by using the tunnelling electrons in an STM to induce luminescence in a dimer formed by two chromophores. Dong explains: "This technique, which combines STM with ultrasensitive photon detection, allows us to map the spatial distribution of the emitted light intensity by precisely scanning over the molecular dimer pixel-by-pixel, obtaining photon maps with sub-nanometer resolution superior to all-optical approaches."

For an emission to be observed, the molecules are deposited on an ultrathin insulating layer to decouple them from the underlying metal substrate, which would otherwise quench an emission. Isolated molecules emit photons with one specific energy; however, when two molecules are pushed next to each other with the STM tip to form a dimer, five different emission modes can be discerned. The researchers show, with the aid of theoretical simulations, that these five modes correspond to the five possible dipole coupling modes of the dimer. The corresponding photon maps thus represent real-space images of the coherent dipole–dipole coupling between the two molecules.

The molecules in the dimer appear to be quantum entangled, meaning that they cannot be described independently but have to be treated as a whole. Indeed, although the tunnelling electrons are injected into only one molecule, the excitation energy is quickly shared with the other molecule and oscillates back and forth between the two.

The researchers finally demonstrated that by forming chains of three or four molecules the excitation is still delocalized over the whole system, and the emission intensity increases with the number of molecules in the chain.

The implications of these results for future research are broad, Dong explains, "ranging from fundamental research on intermolecular interactions to the optimization of light-harvesting systems in photosynthesis and the engineering of electrically driven single-photon sources in quantum optics". Other directions for the development of this work include the study of donor–acceptor energy transfer and molecular quantum-entangled systems that could be used in quantum computing.

Giulia Pacchioni

ORIGINAL ARTICLE Zhang, Y. *et al.* Visualizing coherent intermolecular dipole–dipole coupling in real space. *Nature* **531**, 623–627 (2016)