appropriately sized silver nanoparticles onto the carbon-nanodot surface. Second, electric-field simulations presented by the researchers suggest that the optical fields of closely assembled silver particles on a carbon dot interact and exhibit broad plasmonic activity over a wide spectrum of visible wavelengths, as indicated in Fig. 1.

There are many exciting future directions for plasmon-enhanced solar cells and LEDs. Absorption enhancement within the active layer by surface-plasmon effects can be realized through either direct near-field interactions or by optical-field enhancements arising from forward-scattering processes. These mechanisms depend sensitively on the size, form factor and chemical identity of the metal, as well as the proximity of the metal nanostructures to the active layer[13]. Also critical are the micro- and mesoscopic morphologies, which, if engineered rationally, can influence interparticle interactions, regulate constructive and destructive interference, and ultimately control the spatial optical-field distribution over many length scales[14]. Complex heterostructures may be useful for addressing these issues by providing a platform for realizing bottom-up control of the properties of plasmonic nanostructures. ❐

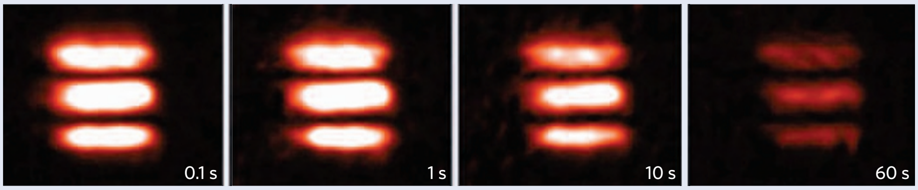
Joseph M. Luther and Jeffrey L. Blackburn are at the Chemical and Materials Sciences Center, National Renewable Energy Laboratory, Golden, Colorado 80401, USA.
e-mail: joey.luther@nrel.gov, jeffrey.blackburn@nrel.gov

References

1. Choi, H. *et al. Nature Photon.* **7,** 732–738 (2013).
2. Li, H., Kang, Z., Liu, Y. & Lee, S.-T. *J. Mater. Chem.* **22,** 24230–24253 (2012).
3. Svedružić, D. *et al. J. Am. Chem. Soc.* **133,** 4299–4306 (2011).
4. Le Goff, A. *et al. Science* **326,** 1384–1387 (2009).
5. Borup, R. *et al. Chem. Rev.* **107,** 3904–3951 (2007).
6. Pylypenko, S. *et al. Energ. Environ. Sci.* http://dx.doi.org/10.1039/c3ee40189h.
7. Westphalen, M., Kreibig, U., Rostalski, J., Luth, H. & Meissner, D. *Sol. Energ. Mater. Sol. Cells* **61,** 97–105 (2000).
8. Huang, J. S., Li, G., Wu, E., Xu, Q. F. & Yang, Y. *Adv. Mater.* **18,** 114–117 (2006).
9. Yang, X. H., Wang, Z. X., Madakuni, S., Li, J. & Jabbour, G. E. *Adv. Mater.* **20,** 2405–2409 (2008).
10. Pillai, S., Catchpole, K. R., Trupke, T. & Green, M. A. *J. Appl. Phys.* **101,** 093105 (2007).
11. Sheehan, S. W., Noh, H., Brudvig, G. W., Cao, H. & Schmuttenmaer, C. A. *J. Phys. Chem. C* **117,** 927–934 (2012).
12. Morfa, A. J., Rowlen, K. L., Reilly, T. H. III, Romero, M. J. & van de Lagemaat, J. *Appl. Phys. Lett.* **92,** 013504 (2008).
13. Catchpole, K. R. & Polman, A. *Appl. Phys. Lett.* **93,** 191113 (2008).
14. Senyuk, B. *et al. Nano Lett.* **12,** 955–963 (2012).

QUANTUM MEMORY

Extended storage times



© 2013 APS

The most promising approach for achieving long-distance quantum communication is to employ quantum repeaters, but they require high-fidelity quantum memories with much longer storage times than the current state-of-the-art memories. The long-term goal of the quantum-communication community is to develop a reliable solid-state optical quantum memory that has a high efficiency, a high storage capacity and long storage times for single or few photons. To realize this goal it is critical to determine the most appropriate medium, the best coherent quantum storage protocol and the most effective control techniques.

Now, Georg Heinze, Christian Hubrich and Thomas Halfmann report light-storage experiments based on electromagnetically induced transparency (EIT) in crystals doped with rare-earth ions (*Phys. Rev. Lett.* **111**, 033601; 2013) and realize storage times close to one minute.

In principle, ion-doped crystals are ideal for use in photon memories because they combine the advantages of solids and isolated atoms with very long hyperfine lifetimes. However, stochastic magnetic interactions with the host material substantially reduce the lifetime of the coherence between the two relevant atomic spin states, which, in turn, reduces photon storage times.

Heinze *et al.* achieved high storage capacities by imprinting two-dimensional image data onto the optical data pulse. In addition, they applied a combination of static and high-frequency magnetic fields to make the medium, a Pr^{3+}:Y_2SiO_5 crystal, less sensitive to external fluctuations, leading to longer storage durations. The applied magnetic fields made the energy level spectrum of the medium very complicated. Consequently, they used feedback-controlled pulse shaping in combination with a self-learning evolutionary algorithm to determine an optical preparation sequence for their medium. According to them, this is the first time that this combined approach has been applied to EIT, quantum memory and the complex level schemes of doped solids in strong magnetic fields. It can also be used to support other storage protocols.

"The most important achievement of our work is the prolongation of the storage time of an EIT-driven memory up to the regime of 1 min. This is very close to the fundamental limit of the population lifetime in our medium, which is 100 s," said Heinze. They also demonstrated the ability to store images in the solid medium for up to 1 min, which is six orders of magnitude longer than the image storage times obtained using hot atomic gases.

"If our approach could be transferred to the single-photon level, it would lead to important applications in the fields of spatially multiplexed optical quantum memory, quantum communications, quantum repeaters and deterministic single-photon sources," Heinze envisaged.

However, their approach has a storage efficiency of only about 1%. The team is planning to overcome this limitation by either optimizing their technique or applying completely different storage protocols. They are also looking at using different media such as Eu^{3+}:Y_2SiO_5, which would naturally provide longer storage durations because of its smaller decoherence effects. They also intend to extend the scheme to the single-photon level.

RACHEL WON