Directing Light Emission from Quantum Dots

Harald Giessen, *et al.*

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nuclear migration defects caused by reducing nesprin2 expression (by siRNA) could be rescued by a "mini" nesprin2 gene that includes the actin-binding and nuclear envelope–targeting domains but lacks the bulk of the spectrin repeats. This suggests that at least for polarizing fibroblasts, the length of nesprin2 is not important.

The strength of the Luxton *et al*. study is the use of live fluorescence microscopy to examine the localization and behavior of actin, nesprin2, and Sun2 during nuclear migration in cultured fibroblasts. It was previously observed that nuclear migration required the rearward flow of actin speckles (*10*). Luxton *et al*. now describe an array of actin cables that forms on the dorsal surface of nuclei, parallel to the wound edge, within 30 min after induction of polarization. The cables moved away from the wound edge at the same rate as nuclei. Both nesprin2 and Sun2 were recruited to, and moved with, the actin cables to create TAN lines. TAN lines therefore contain all the components needed to bridge the nuclear envelope and couple the nuclear lamina to the cytoskeleton.

TAN lines have parallels to other complexes that connect actin assemblies to structural components on the opposite side of a membrane. For example, both focal adhesion complexes and the dystrophin complex span the plasma membrane, connecting actin filaments to the extracellular matrix. There are further similarities between nesprin2 and dystrophin—they have homologous actin-binding domains and spectrin repeats (*2*). In budding yeast, actin movements just outside the nucleus are coupled to rapid movements of chromosome ends (telomeres) during meiosis. A SUN protein is required for this coupling, which suggests that the assembly of TAN line–like structures at the nuclear surface might be conserved (*11*). Future studies are required to determine whether TAN lines exist in three-dimensional tissues and how broadly such structures are used in the positioning of nuclei.

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PHYSICS

Directing Light Emission from Quantum Dots

The photon emission from a semiconductor quantum dot directed by a nanoscale gold antenna could be used in quantum optics.

Harald Giessen[1] and Markus Lippitz[2]

Cell phones, radios, and television sets contain antennas that pick up signals carried by electromagnetic radiation and convert them into pulses of electric current. Antennas connect two very different length scales—transmission wavelengths range from centimeters to meters, whereas component wiring and circuitry is on the micrometer-to-millimeter scale. On page 930 of this issue, Curto *et al*. (*1*) take this scaling concept to the optical world, where the interaction of light with matter includes quantum mechanics as well as classical electromagnetism. They fabricate nanoantennas from gold, a metal that can develop charge oscillations in its surface layers when excited by optical radiation. These antennas allow visible radiation, which has wavelengths of hundreds of nanometers, to couple into a semiconductor quantum dot only a few nanometers in diameter, and also direct the emission.

The value of a good antenna is best appreciated when a damaged antenna cable turns a TV picture into a snow pattern. A temporary repair can be made by removing the faulty cable and sticking a screwdriver into the antenna plug. The reception will be somewhat grainy, but at least you can watch some programs. The reason for the poor picture quality is what electrical engineers call mode or impedance mismatch. The temporary antenna is not mode matched to the electronic circuits, so much of the signal fails to get into the circuits—it is reflected back into the screwdriver antenna. TV antennas are mode matched not only to the electronic circuitry, but also to electromagnetic waves, which travel through free space.

Antennas can be omnidirectional—for example, the simple dipole antenna that folds out from a portable radio. A very common TV antenna, the so-called Yagi-Uda antenna, invented by Yagi and Uda in 1926, is directional (see the figure, panel A). It can be tuned to pick up weak signals efficiently from distant transmitters. When used in transmitting mode, it can direct the outgoing beam into one direction about 5 to 10 times more efficiently than a dipole antenna.

Quantum emitters, such as atoms, molecules, and quantum dots, can also be regarded as extreme subwavelength "circuits." An electrical engineer would regard them as rather bad transmitters or receivers of radiation, because their extremely small size does not offer good mode matching to the dipole mode of the light to which they couple. Good mode-matched antennas reradiate their energy after excitation within a single cycle of the wave. Molecules or quantum dots take nanoseconds or even longer to reradiate their energy. This time scale corresponds to about 1 million oscillations at optical frequencies, and the emission is in all directions.

It is possible to fashion nanoantennas from metals such as gold that can bridge the mode-matching gap in the optical regime because they can reradiate their energy within femtoseconds (*2*). The very large oscillator strength of the antennas enables better coupling and faster response to the propagating dipole fields of free space compared to a quantum dot. Gold has a very high density of charge carriers—electrons and holes—oscillating back and forth at the so-called particle plasmon resonance. Each electron-hole pair can be viewed as a single dipole, and there are several millions of them in each nanoantenna of about 100-nm diameter.

If an atom, molecule, or quantum dot is placed into the near-field of a metallic

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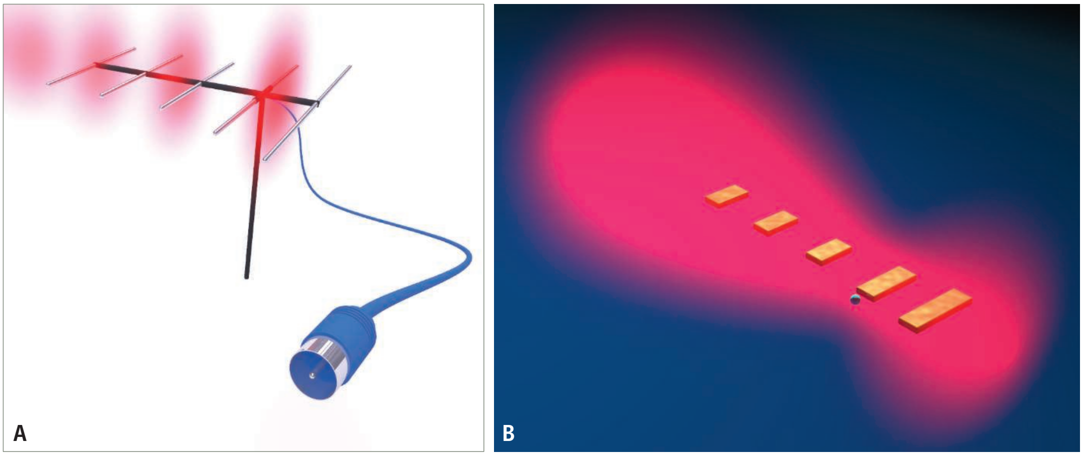
nanoantenna (within about 1/50th the wavelength of the emitted radiation), its excited state can radiate photons very efficiently to free space (see the figure, panel B). The quantum emitters can emit a single photon, which can be exploited in quantum optics. Additionally, the nanoantenna can redirect radiation into a defined solid angle in space and impose a specific polarization on it.



Antennas large and small. (**A**) A Yagi-Uda TV antenna is shown with feed, reflector, and directors, as well as its radiation pattern. The radiation is fed with very high efficiency into the antenna cable and connector, which are much smaller than the wavelength of the broadcast signal. (**B**) Curto *et al*. coupled the emission of a single quantum dot to a gold Yagi-Uda nanoantenna. This coupling increases the rate of photon emission and makes the emission pattern highly directional.

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Until now, quantum emitters have mostly been coupled to rather simple structures, such as the metallic tip of a scanning probe microscope (*3*), simple metallic nanodots or nanowires (*4*, *5*), gap antennas (*6*), or bowtie antennas (*7*). Curto *et al*. have manufactured metallic nanoantennas of different shapes, namely nanodots and nanowires, as well as directive Yagi-Uda antennas (*8*). They then positioned quantum dots near the antennas using an elaborate two-layer nanolithography scheme. The authors excited the quantum dots with a laser beam and observed blinking emission, a strong indication that only a single quantum dot was attached to the antenna. The emission pattern of the dot near the antenna is governed by the nanoantenna, as is the polarization of the emitted light. Especially convincing is their analysis of emitter coupling to the nanoantennas when the antenna's plasmon frequency matches that of the emitter (that is, it is in resonance, versus off resonance). By carefully preparing many different-sized structures, they show that the quantum dot emission is highly directional and polarized only under resonance conditions.

The approach developed by Curto *et al*. could lead directly to several important advances. Photon antibunching, in which photon emission is more equally spaced in time than with a light-emitting diode, could create an effective single-photon source for quantum communication that emits the single photons efficiently into a narrow beam. The demonstration of the Purcell effect, which is the acceleration of the decay of the quantum emitter caused by impedance matching by the antenna to free space, could also enhance the radiative emission over nonradiative losses.

The technology itself could be further improved, for example, by using an antenna array to gain even higher directivity or to scan the beam in several directions as is done with phased-array radar. Two nanoantennas could face each other to create an optical nanoantenna link (*9*) and, eventually, demonstrate antenna- or plasmon-based controlled coupling of two quantum emitters to show quantum interference. If the quantum emitter used was a nitrogen-vacancy center in diamond (*10*), a true room-temperature quantum computer could become a reality when exploiting the different spin states.

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GENETICS

Replication Error Amplified

Salma Kaochar, Andrew L. Paek, Ted Weinert

Yeast offers insight into how lifting controls on DNA re-replication can cause cells to make extra copies of a gene.

Cells have a seemingly endless array of regulators to provide for fast and accurate DNA replication. Most cells succeed in doing it right, each and every time they divide, which is testimony to the powers of evolution. Failure to limit DNA replication to just once every cell cycle can lead to genome rearrangements, in particular to "amplification," or an increase in the number of copies of some genes. Amplification can drive abnormal cell growth, and cancer cells often have amplified oncogenes (*1*). How gene amplification occurs, however, is unclear. One mechanism involves the breaking and fusion of aberrant chromosomes, a process first discovered by Nobel Laureate Barbara McClintock in the 1950s (*2*), which leads to extra copies of genes that are joined together (*3*). Another proposed mechanism involves defects in the "re-replication" controls that shut down the DNA-copying process after a single duplication, but this idea had not been testable (*4*). On page 943 of this issue, Green *et al*. overcome that hurdle with an extravagant experimental system in budding yeast that demonstrates that re-replication is indeed a potent mechanism of gene amplification (*5*).

These authors have been studying the labyrinth of controls that normally prevent re-

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