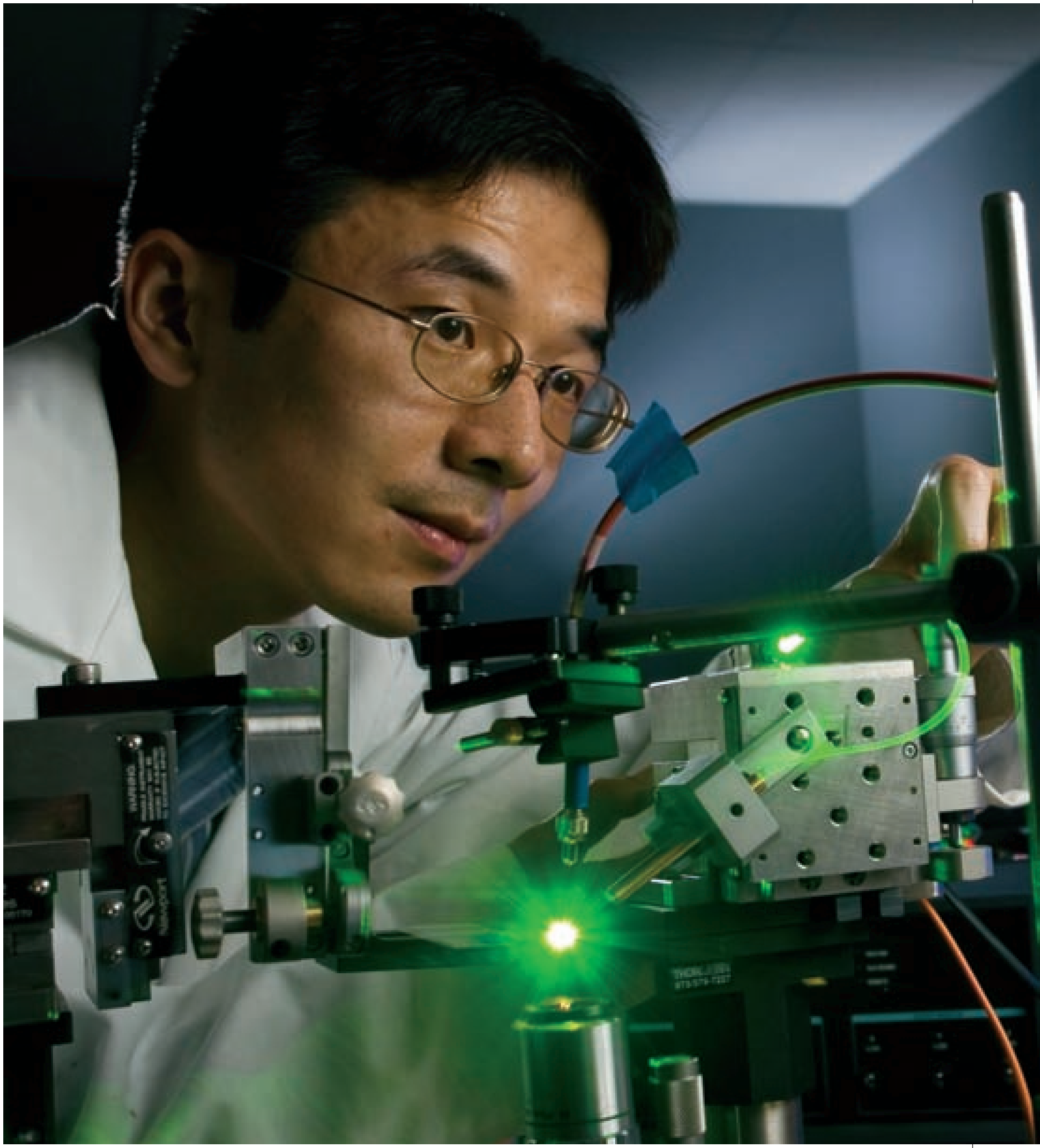
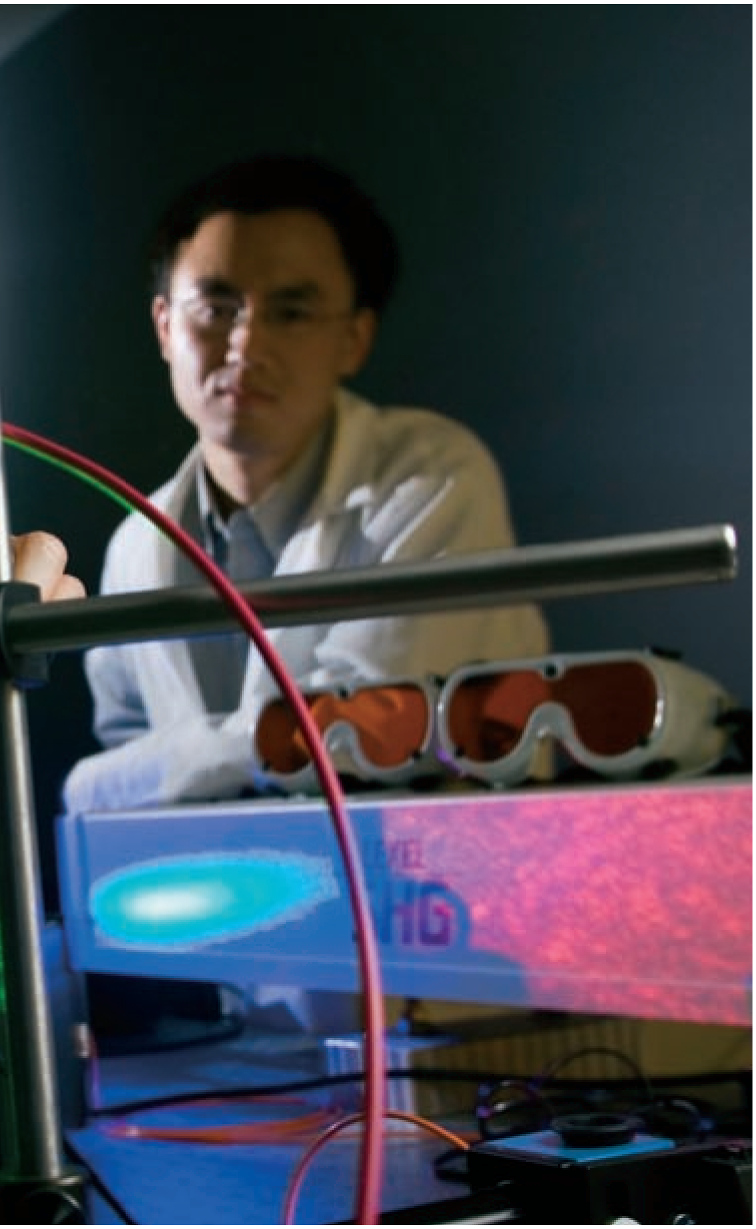
Making the smallest things visible

NANOPROBING



Yong Xu (left) is developing technology that employs a nanotube on the end of a fiber to achieve an optical imaging resolution of 1nm. His team uses a laser imaging system in order to “see” and manipulate the nanotubes. Graduate student Yaoshun Jia observes from the right.

Nanoprobe technology could achieve ultimate optical imaging resolution, while helping explore one of the last mysteries of quantum electrodynamics



Yong Xu, an assistant professor of electrical engineering, is developing an active nanoprobe technology that could enable significant breakthroughs in optics, physics, and communications.

Optically, his nanoprobe technology can break the diffraction limit and achieve the ultimate optical imaging resolution of 1 nanometer. Furthermore, he hopes to use the nanoprobes to measure one of the few remaining mysteries of quantum electrodynamics—vacuum field fluctuations. The probe could also be configured as a single-photon emitter, enabling quantum cryptography and the ultimate secure communications link.

Xu has received a National Science Foundation (NSF) Faculty Early Career Development Program (CAREER) Award to support his efforts. CAREER grants are NSF's most prestigious awards for creative junior faculty members who are considered likely to become academic leaders.

A tube and a dot

The potential of Xu's technology seems inversely proportional to its size—that of a single carbon nanotube. A carbon nanotube is a single-atom-thick sheet, shaped as a cylinder, that can have a diameter of about 3 nm. Its length can reach tens of microns. Like many nanoscale molecules, carbon nanotubes have novel properties, including great strength and numerous intriguing electrical properties.

While a nanotube will serve as the body of the probe, the tip of an optical nanoprobe will be a single 1-3 nm quantum dot and the whole assembly attached to an optical fiber. Also called nanocrystals, quantum dots are nanometer-scale pieces of semiconductor that can emit light (fluoresce). "We needed an emitter with a size as small as possible," Xu explains. "We also needed a fluorescent element that is bright, stable, commercially available, and can cover a broad wavelength range."

Xu expects it may take up to two years to perfect the fabrication techniques and develop working prototypes of the appropriate size and strength. Once the fabrication is proven, his team will apply the nanoprobes in near-field imaging, vacuum-field imaging, and single-photon generation.

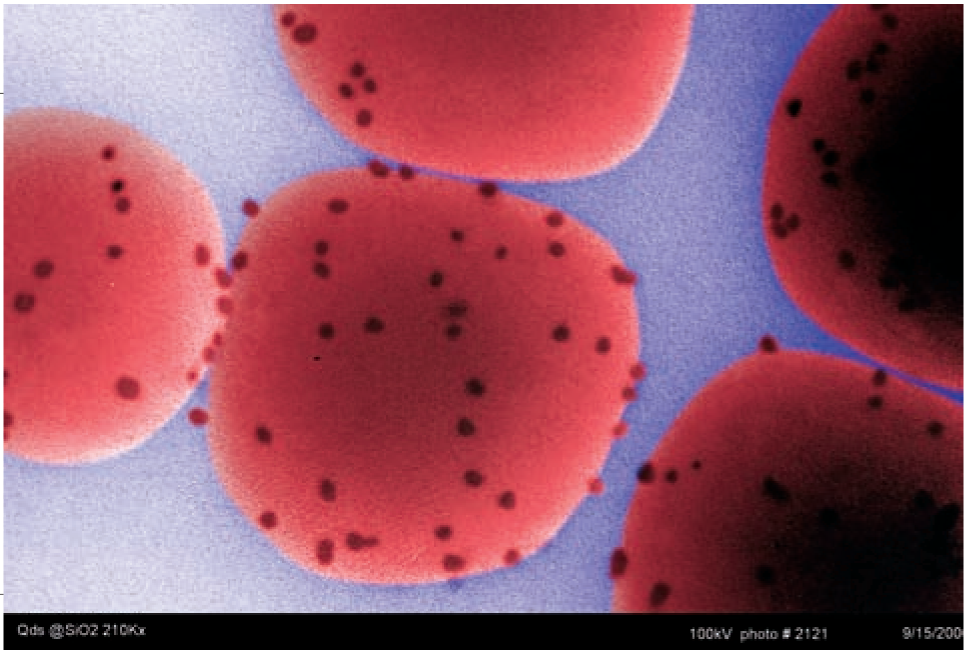
Improving the optical microscope

"Improving resolution is critical to the advance of nanotechnology," Xu says. "We need to be able to image optical

Colorized images of nanotechnology
From the left: Quantum dots (dark spots, ~3nm in diameter) on silicon nanospheres (red).

Center: An army of Bragg onion resonators, similar to the ones Yong Xu plans to use to demonstrate and map vacuum field fluctuations—which have been proven, but never mapped.

Far right: a close-up of the resonator shows the layers of "shell," which make it possible to isolate a vacuum field fluctuation.



structures and observe physical phenomena at ever smaller sizes."

Most optical microscopes are restricted by the diffraction limit and cannot produce optical images with resolutions better than a few hundred nanometers. To overcome the diffraction limit, the current approach relies on a nanoscale fiber aperture to obtain higher imaging resolution, as in the case of near field scanning optical microscopes (NSOM). However, even in the most advanced NSOM systems, the imaging resolution is limited to about 50 nm resolution. In addition, NSOM technology relies on metal-coated tips, which creates a large perturbation of the original optical field, Xu explains.

Since the ultimate resolution limit of nanoprobe imaging is determined by the size of the fluorescent element, Xu's nanoprobe should enable optical imaging at a resolution of 1-3 nm, he says. The probe can generate images by scanning the position of the quantum dot and detecting the fluorescence into the silica fiber. "Using a single carbon nanotube, the nanoprobe can achieve for the first time non-perturbing imaging at this resolution," he says.

Viewing a quantum mystery

With a nanoprobe of such small scale, Xu hopes to demonstrate a 3-dimensional vacuum field imaging for the first time. Modern physics has determined that a vacuum is not a complete void, as many people believe, he says.

"By definition, there is always something there, even in the absence of all particles. We call this tiniest level of physical existence of electromagnetic field 'vacuum field fluctuation.' Light, contrary to what you might imagine, comes as waves of tiniest energy bundles called 'photons.' And a photon is emitted when an atom or a molecule jumps from a high energy level to a low level," he explains.

"If there is no electromagnetic vacuum field, then they won't jump. There is a perturbation that in essence tries to trick them into jumping from high to low. Our most precise theory of nature predicts this and we know it must be there because otherwise our devices would not work. We have verified vacuum fields by countless experiments. We have a theory to calculate it, but we have not been able to measure what is going on and how it is distributed," he says.

Xu plans to analyze the decay of the quantum dot to measure a vacuum field. "The decay of the light emitting process indicates there is a field. By measuring how it decays or how quickly a photon is emitted, we can infer the distribution of the field."

The nanoprobes in this application will have a tip of multiple quantum dots. In addition, an integral part of the 3-D vacuum field imaging is the use of silicon-based Bragg onion resonators he helped develop while he was a postdoctoral scholar at Caltech.

New, single photon emitters

The third application of the nanoprobes is to convert them into single-photon emitters, which can be used in quantum cryptography

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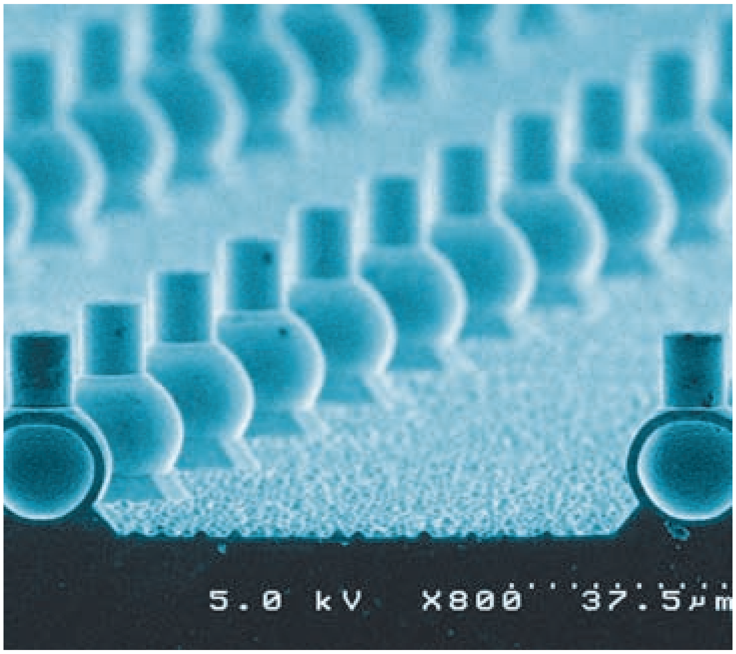

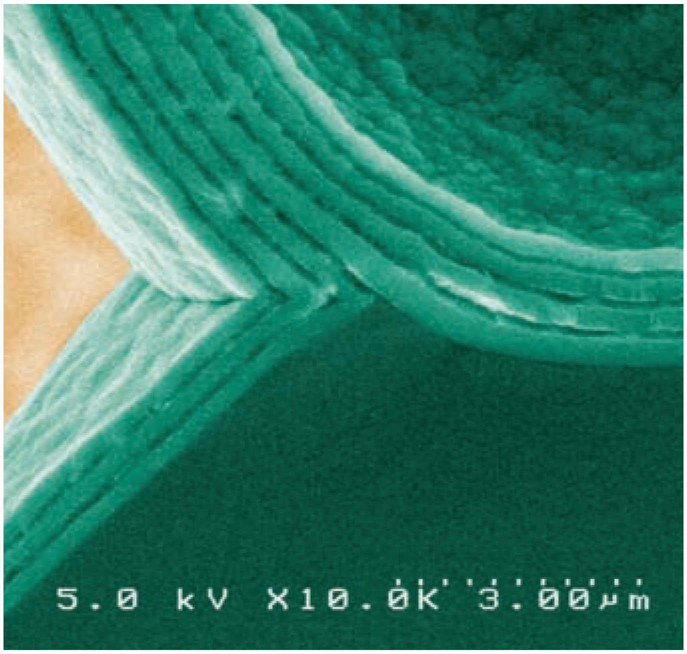

and quantum information processing.

"In our approach, we use a nanoprobe to achieve optimal coupling between a single quantum dot and a cavity, so that single photons can be triggered as needed," he says. "We can engineer the cavity so that all the photons generated by the quantum dot will go into the cavity. In the end, we can create a 'push button' device that can generate one, and only one, photon at a time, i.e., single photon on demand."

A reliable, constant source of single photons will enable the development of quantum cryptography, where the security of communications is guaranteed by one of the most basic laws of nature. "A photon cannot be split in two, which is a wonderful gift of life." Xu says. "A photon is either detected or not detected. It is a signal of one. It is either received or stolen by an eavesdropper." If sidetracked by an eavesdropper, the recipient knows the data or message is compromised.

The trouble with tiny

Xu's nanoprobe technology in imaging, computing, measurement, and communications, may find future use in physics, biology, chemistry, and even quantum teleportation, he suggests. However, in the near-term, his team faces challenges related to the small size of the technology.

"We deal with structures with dimensions of a few nanometers, so we must make sure everything is perfectly stable and nanostructures are precisely manipulated," he explains. "We are also working with one photon at a time. That is a very weak signal. We need to detect something so incredibly weak and still isolate it from the noise. We spend a lot of time in a dark room."

Calling on an army of onion resonators

For Yong Xu, 3-D vacuum field imaging is one of the most important aspects of his research. "It is a great challenge and great fun to be able to measure something that has never been measured before to the precision of a few nanometers," he says.

Not only would success reflect the first time vacuum field imaging is demonstrated, but Xu's work may also lead to the creation of a silicon laser, which is the most critical missing component in the race towards silicon-based integrated optics.

Xu's team plans to demonstrate vacuum fields by using Bragg onion resonators he and his colleagues at Caltech and Sandia National Laboratories developed in 2004. Each resonator is a hollow cavity encased in a shell made of alternating layers of high-index silicon and low index silicon dioxide (SiO_2). Each resonator has a "stem" opening so that a nanoprobe can be inserted.

The shell is a very thin 250 nm and each resonator is 10 to 15 microns in diameter. Due to the large index contrast between silicon and SiO_2, the shell can behave as a perfect conductor and provide 100 percent reflection for any incident light. This can effectively isolate the vacuum field in the hollow core from outside field.

Xu's team has developed a theoretical model and demonstrated that onion resonators can both enhance and inhibit spontaneous emission by more than one order of magnitude. "This tells us we can funnel most of the spontaneous emission into the desired mode, which is important for both single photon sources, and for laser applications," he says.