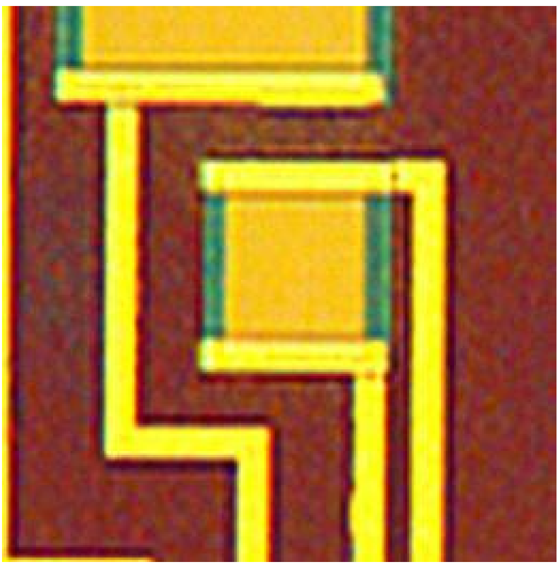
Adding up photons with a transition edge sensor

November 14 2011, By Thomas Gerrits



At the center of this micrograph, the TES is the orange-and-green square between two bright gold electrodes. Its dimensions are 25 X 25 µm. Credit: NIST/PML

(PhysOrg.com) -- Scientists have demonstrated that a superconducting detector called a transition edge sensor (TES) is capable of counting the number of as many as 1,000 photons in a single pulse of light with an accuracy limited mainly by the quantum noise of the laser source.

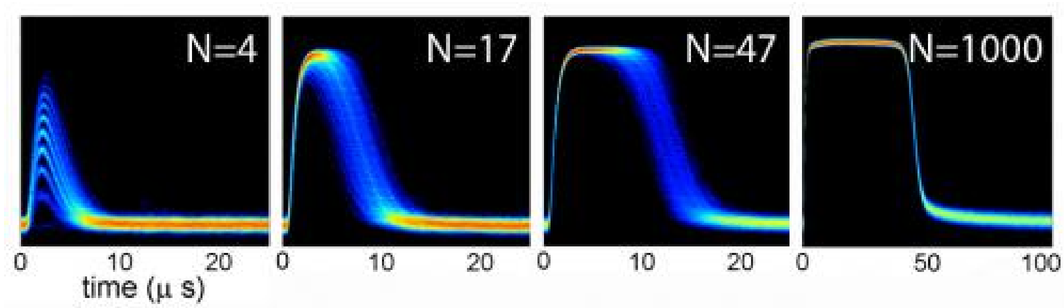
The findings, which are being prepared for publication, could eventually find use in quantum information processing, telecommunications and optical metrology at low light levels when information is embodied in readily detectable numbers of photons.

"When the uncertainty of the photon-number determination is sufficiently low and the detection efficiency is close to unity, by detection one can decode information that was encoded in the amplitude (photon number) of a pulse of light," says Thomas Gerrits of PML's Quantum Electronics and Photonics Division, a member of the research group which includes researchers from PML's Quantum Measurement Division.

Many detectors can sense single-photon pulses, and some (including the TES) can even resolve a few tens of photons in a single pulse. Accurate counts above approximately 50 photons, however, have not been achieved until now. The new PML research extends the photon-number resolution range as high as 1,000 and dramatically decreases the associated measurement uncertainties.

A TES consists of a thin layer of superconducting material (in this case, a tungsten film 20 nm thick) placed on an insulating substrate (in this case, silicon). The entire device, measuring 25 X 25 µm, is cooled below the critical temperature of the superconducting film. But a small voltage is applied across the film, so that it has a slight electrical resistance and is in the middle of its superconducting transition region—that is, neither a superconductor nor a conventional conductor.

Every time an incident photon strikes the device, the photon's energy is absorbed, heating the superconducting film and raising its resistance. When a very large number of photons are absorbed, the heat saturates the device, forcing it past the transition edge and well into normal (non-superconducting) regime.



This series of data read-outs shows how the TES relaxation time increases with photon number. For N=4 photons, the TES returns from the elevated-resistance state to the edge of the transition region in less than 10 μs. At N=47 photons, it takes around 15 μs. And when the count is 1000, the relaxation time is approximately 50 μs.

"NIST has been advancing the use of transition-edge sensors from detecting terahertz radiation to gamma rays," says Sae Woo Nam of PML's Quantum Electronics and Photonics Division. "We've been focusing on the use of these sensors to detect near-IR/visible light. In particular, we've been making photon-number-resolving detectors for nearly a decade now. We're exploring an operating region that may help us understand how to link measurements of optical power made by different devices at different power levels more accurately."

The PML/JQI team was interested in knowing how well a TES could resolve larger photon numbers that drove it beyond its saturation point. They kept their TES near 140 mK, in the transition edge temperature region, and then irradiated the device with bright laser pulses of 1550 nm wavelength at a frequency of 1 kHz.

But instead of simply measuring the change in resistance, as is done to resolve the photon number in faint pulses of light, the scientists measured the thermal relaxation time—the amount of time it takes the

TES to shed its heat and return to the upper edge of the transition region. That time interval, they found, is a remarkably sensitive indicator of photon numbers up to about 1,000. (See illustration at bottom of page.) For brighter pulses, substantial heating of the substrate occurs, and numbers cannot be as accurately resolved.

Given those data, it might seem a relatively straightforward matter to find a mathematical relationship between relaxation time and photon number, thus producing a working scale. And, in fact, the group devised a model that fit the data extremely well for numbers between 100 and 1000, accurately describing the results of 20,000 individual tests for each of several different photon numbers. Another technique yielded the correct values for numbers between zero and 30. The scientists are still at work on a single model that will combine those measurements.

There are planned practical applications for the findings. "Where low levels of light are present and high detection efficiencies with low uncertainty are required, we can make use of this detection scheme," Gerrits says. "Low-light-level homodyne detection for optical quantum states is such an application that we are planning to develop in the near future. It requires high detection efficiency and low uncertainties (noise). Generally one uses large amounts of light and commercially available photodiodes to perform homodyne measurements. However, the photodiodes that are available today do not have high detection efficiency and low noise in the telecom band. Thus for states that are generated in the telecom band, this detection scheme might be of good use."

In a broader sense, expanding the dynamic range of single-photon detectors advances a long-standing goal: to develop radiometric metrology tools that allow for more direct and better connections between existing radiometric standards that require high levels of light and single-photon metrology standards.

The scientists are now examining ways to reduce the photon-number uncertainty even further. One way would be to employ a light source that can dependably produce a highly exact number of photons. That means moving beyond the laser pulses used in the first set of experiments. One promising candidate source is a process called parametric down conversion, in which a single photon traveling through a nonlinear crystal is converted to two photons whose combined energy and momentum equals the original.

"PDC has been the basis of a single-photon source, because detecting one photon of the pair – which serves to 'herald' its partner – guarantees that one and only one photon exits the source's output channel," says Alan Migdall of PML's Quantum Measurement Division.

"But it is also possible to make an N-photon source. The idea is to operate the PDC process to produce many pairs at once. If the TES can tell how many photons have arrived in the heralding channel, then we can know the exact number of photons in the other channel. Such a PDC-based N-photon source offers a much lower uncertainty than lasers can provide. Thus the TES can be used to make an improved light source that is a needed tool to characterize the improved performance of the TES itself, which is way cool."

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