Calibrating an optical attenuator with few-photon pulses

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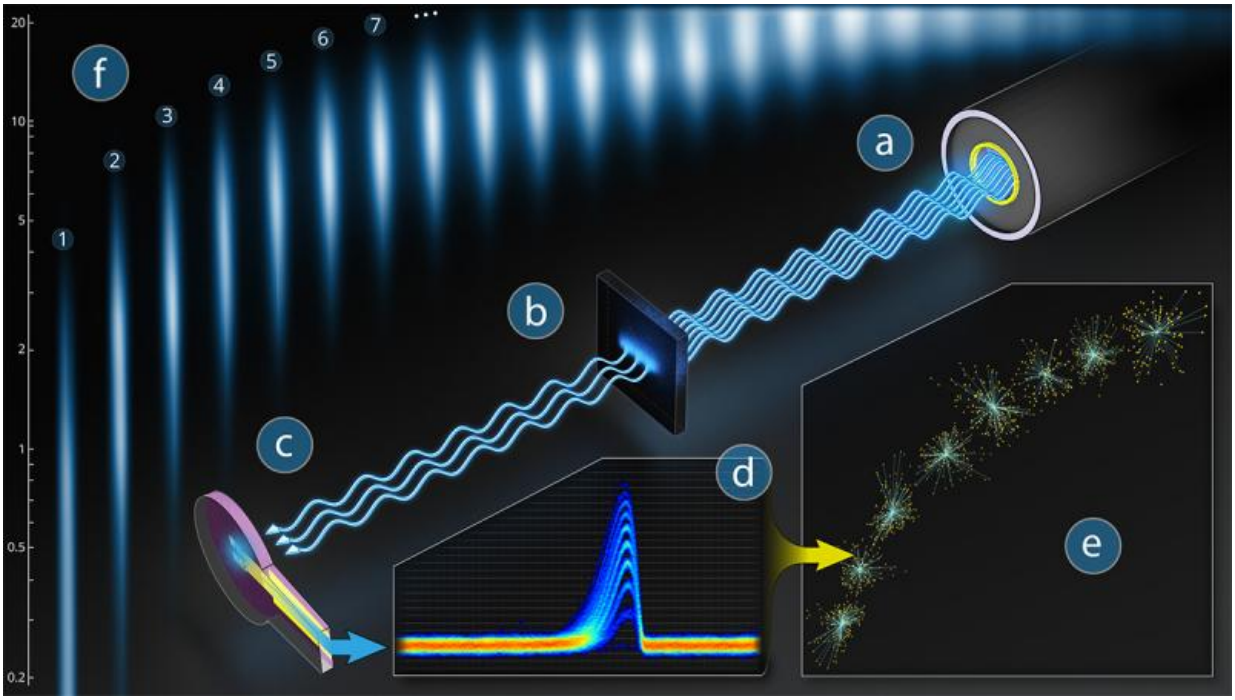

Light from a pulsed laser (a) is directed through a variable attenuator (b) onto a transition edge sensor device (c). The resulting signal (d) is analyzed with a statistical clustering algorithm (e) which returns a nominal photon number (f).

Precise measurements of optical power enable activities from fiber-optic communications to laser manufacturing and biomedical imaging—anything requiring a reliable source of light. This situation calls for light-measuring (radiometric) standards that can operate over a

wide range of power levels.

Currently, however, different methods for calibrating optical power measurements are required for different light levels. At high levels, existing radiometric standards employ analog detectors, diodes that generate a current proportional to the incident light intensity, but become imprecise at low levels. Low-power detectors, by contrast, very accurately measure discrete (usually very small) numbers of photons, but cannot handle light at higher levels. Because of the incommensurate scales and incompatible technologies, comparison between the two kinds of measurements isn't easy, resulting in long calibration chains to span the difference.

Linking standards for widely different powers requires extending the dynamic range of detection to cover the region between the two measurement regimes. There are two options for bridging this gap: a "top-down" approach using analog detectors and a "bottom-up" method that starts with counting individual photons.

Exploring the second option, a team of JQI scientists, along with colleagues from NIST's Physical Measurement Laboratory (PML), has demonstrated a technique for extending the range of photon-counting detectors by employing optical attenuators, devices that block controlled fractions of incoming light. The results, recently published in *Optics Express*, could lead to improved standards to cover a much wider range of optical power.

The benefit of anchoring standards to detectors capable of counting single photons is a matter of precision, explains team member Boris Glebov.

"Measuring frequency of light is probably the most precise measurement science can perform," Glebov says. "Thus, if you have a way to link

power measurements to photon counts and frequency measurements, the possible precision is incredibly high."

Knowing the energy of each photon (a function of its frequency) and the number of incident photons enables an extremely accurate determination of optical power. This is because photon counting has inherently low uncertainty, says JQI fellow and Quantum Optics Group leader Alan Migdall.

"A single-photon detection scheme means we are counting discrete things, so in principle the error goes away," Migdall says. "Either we have a count or we don't."

Over the past few years, Migdall's group has focused considerable effort on developing better ways to count individual photons. In particular, they have worked on improving the performance of a superconducting detector called a transition edge sensor (TES), using devices developed and produced by Sae Woo Nam and colleagues from PML's Quantum Electronics and Photonics Division at NIST's Boulder, Colo., campus.

A transition edge sensor contains a tiny superconducting circuit. When a photon strikes the superconductor, its energy is absorbed in the form of heat. The rise in temperature causes an increase in electrical resistance and a corresponding drop in current, which registers in the detector electronics. The devices provide excellent photon number-resolving capabilities and can operate over a wide range of frequencies, from radio waves to gamma rays. However, the number of photons has been limited, typically to about 20 photons or fewer. In order to use TES devices at higher optical power levels, the operating range needs to be extended.

Previously, the scientists approached this problem by modeling the relaxation time (the time it takes for the sensor to cool down after absorbing photons) and developing certain algorithms for better

processing the output signal from the device. This has enabled them to extend the devices' sensitivity range to as high as 6,000,000 photons in a single pulse.

To extend it even further, the scientists devised a method in which a TES is used to calibrate its own input attenuator. This device provides variable optical attenuation—the selective reduction in the light power that passes through it. Controlled attenuation of high-power light merged with a photon-counting detector could connect the high precision offered by photon-counting measurements to measurements made at higher illumination levels.

To perform the calibration, pulsed laser light is directed through a variable attenuator, which is gradually stepped through a series of attenuation values. The resulting signals from the TES are processed by an improved version of the group's algorithm, enabling accurate statistical determinations of the photon number at each value. Comparing the change in the measured photon number as the input attenuator is adjusted allows the attenuator to be calibrated in place. Significantly, the approach doesn't require knowledge of the power of the light source, which means no external calibration is necessary.

Since the ratio by which an attenuator reduces the power of a signal is independent of input power (up to some limit), measurements of attenuation made at the few-photon level should agree with those made at much higher intensities. To confirm this, the researchers compared the values obtained with a TES to those obtained with a conventional analog power meter. In every case, the measurements agreed within a small statistical uncertainty.

"Even though we calibrate at the few-photon level, these attenuators can be used at higher powers, extending the utility of a TES well beyond its own operational range," Glebov says. This means a TES-calibrated

attenuator can be used to compare detectors, regardless of the optical power they are designed to operate at. In essence, the low uncertainty now associated with the calibrated attenuator can be transferred to other devices, enabling comparisons between standards through relative measurements.

A TES could also be used to calibrate a series of attenuators with only a small increase in combined uncertainty, enabling an even larger range of operation. The ability to dynamically extend the operating range of a TES in situ—without reliance on external standards or needing to reset optical components—could prove useful in situations that by necessity operate at the few-photon level, for instance in quantum key distribution. Aside from extending the operating range of TES detectors, improved determination of optical attenuation could help when characterizing materials that react differently to high- and low-light levels or with samples that can survive only low-light levels, for instance when analyzing sensitive biological samples.

More information: Zachary H. Levine et al. Absolute calibration of a variable attenuator using few-photon pulses, *Optics Express* (2015). DOI: 10.1364/OE.23.016372

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