Correlated-Photon Metrology without Absolute Standards

The quantum correlation of paired photons produced in nonlinear optical crystals promises metrologists something of a free lunch: absolute measurements that don't require absolute standards.

Alan Migdall

Just like human twins who evoke amazement and a sense of mystery by reporting empathetic experiences across great distances, photons born in pairs also astonish us by their quantum-correlated behavior.

Photons created two at a time with entangled quantum states are odd beasts. Because our intuition is used to dealing with individual things, we are easily surprised and baffled by what are inherently and irreducibly two-particle objects. Two-particle correlation and entanglement have a long history of highlighting the most fundamental and unsettling aspects of quantum mechanics, such as non-locality.

Although two-particle entanglement has received much attention for its fundamental aspects (see PHYSICS TODAY, August 1993, page 22; February 1998, page 18; and July 1998, page 36), these systems have not been widely recognized for their equally surprising and useful applications in the field of metrology. Two-photon states allow us to perform absolute optical measurements without relying on any externally calibrated standard.

This kind of metrology, based on quantum-correlated photons, has the appearance of getting something for nothing. Specifically, the techniques include methods for determining the absolute quantum efficiency of detectors without any calibration standards and measurements of absolute infrared spectral radiance, again without any previously calibrated standards and without even an infrared detector! (Spectral radiance is optical power per unit area, per steradian and per unit bandwidth.) Another such technique under investigation lets us make subfemtosecond timing measurements with only nanosecond electronics and continuous-wave lasers.

Parametric down-conversion

All of the applications discussed in this article rely on the process of optical parametric down-conversion, illustrated in figure 1. Photons from a pump laser beam decay into pairs of photons within a suitable optically nonlinear crystal. (See the article by Martin Fejer in PHYSICS TODAY, May 1994, page 25) This decay is, of course, constrained by conservation of energy and momentum:

$$\omega_{\mathrm{p}} = \omega_1 + \omega_2$$

$$\mathbf{k}_{\mathrm{p}} = \mathbf{k}_1 + \mathbf{k}_2 \,,$$

where ω and $\mathbf{k}$ are photon frequencies and wave number vectors (within the crystal); the subscripts refer to the pump beam and the resulting pair of down-converted photons.

Because of these constraints on the simultaneous creation of a pair of photons, it is clear that knowledge of the pump beam and one of the output photons provides information about its companion. More precisely, it provides information as to what *would* be the outcome of certain measurements on that second photon, if those measurements were made. Not only does the detection of one photon indicate the existence of a second photon, but the emission time, wavelength, direction and polarization of the one tell all about the other.

The parametric conversion of a single photon into a pair, as we have described it so far, is essentially a spontaneous decay process.[1] But it can also be stimulated by the introduction of an additional seed-light beam into an output channel (as in figure 5). That is the typical configuration of an optical parametric amplifier. In amplifier terms, the spontaneous production of light is an output without an input. As we shall see, the relation of this strange spontaneous output to the amplifier output stimulated by seed light is also the basis of a new metrological technique.

Absolute detector calibration

Complete knowledge of a particular photon leads naturally to the first metrological application we shall discuss: the measurement of a detector's absolute quantum efficiency. Detector quantum efficiencies were already being measured by David Burnham and Donald Weinberg in 1970, in the very first experimental demonstration of the timing correlation between pairs of simultaneously created photons.[2] The arrangement for such a measurement, as shown in figure 2, consists of placing a pair of detectors so that they pick up each photon of a down-converted pair. Detector B can be regarded as the trigger; its firing indicates the presence of a photon. Because the photons have to be created in pairs, there must also be a photon incident on detector A. So for every detection at B, we look to see if there is, in coincidence, a photon detected at A. The quantum efficiency of detector A will then be just the fraction of B detections for which a photon is also detected, in coincidence, at A.

To determine the quantum efficiency of A, one doesn't have to know the efficiency of the trigger detector B. Some photons incident on B will not be detected; the trigger will not be perfect. But that does not affect the calibration of A, because we do not look at A if the trigger is silent. Of course, we could just as well calibrate detector B by

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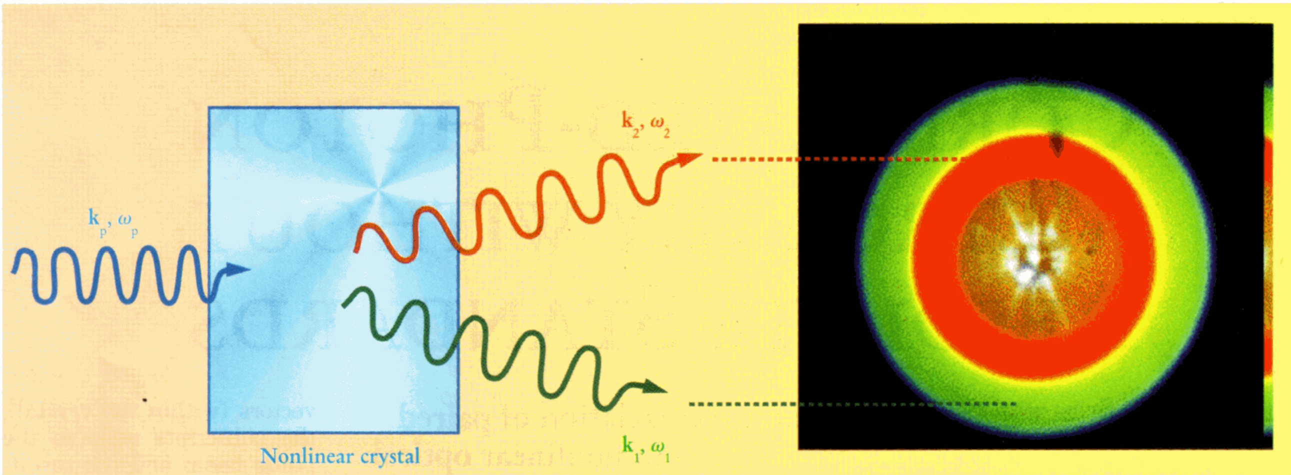

FIGURE 1. PARAMETRIC DOWN-CONVERSION, turning a single photon entering an optically nonlinear crystal into two photons coming out, is essentially the inverse of sum-frequency generation. The energy $\hbar\omega$ and momentum $\hbar\mathbf{k}$ of the incident photon equals the sums of the outgoing energies and momenta. The concentric circles of output light in different colors (at right), azimuthally symmetric about the monochromatic pump-beam axis, indicate the broad spectral range of the down-converted light. At their center, one sees some of the pump light leaking around a beam stop.

treating A as the trigger, or we could calibrate both detectors simultaneously. Although there are a few subtleties that have to be mentioned (see box 1 on page 44), this technique really is inherently absolute. Absolute measurement, without reliance on distant standards, is one of the most sought-after goals in metrology.

A variant of this method could even eliminate the second detector altogether. The detector under test becomes its own trigger. This would be accomplished by directing both photons of a pair onto the same detector, with an appropriate optical delay for one of the paths, and autocorrelating the output of that detector—instead of cross-correlating the output of two different detectors. So now one needs neither a calibrated standard nor even an uncalibrated second detector.

The down-conversion process is nonresonant—it uses no optical buildup cavities. Therefore, output pairs are produced with a wide range of wavelengths, as seen in the photo in figure 1. This latitude makes it possible to use two detectors operating in very different spectral ranges. So, if the detector to be calibrated is designed for some difficult spectral regime, the trigger detector can be chosen for a more convenient region—usually in the visible.

The fact that the calibration wavelength of the detector under test is determined by the wavelength of the photons seen by the trigger detector makes possible another advantage of this technique. All of the spectrum-limiting optical elements can be placed in the optical path of the trigger channel. That way, one doesn't have to determine the transmittance of the spectrally selective element. It's as if there were a virtual spectral-bandpass element with peak transmittance normalized to unity in front of the detector being tested—an ideal situation for a metrologist.

A continuous-tuning realization of this capability would be a setup with a monochromator in the trigger path. (See figure 3.) By varying the central wavelength and passband of the trigger monochromator, one selects the wavelength and passband of detector A.

An alternative view

This method of absolute calibration without standards is remarkable. But it can be viewed in another equally striking way. Taken together, the pump laser, crystal and trigger detector can be thought of as a fundamentally new type of absolute light source—one whose output can be calculated from first principles and fundamental constants. (See figure 4.)

Such an absolute source is fundamentally different from the other two types of absolute sources we have: blackbodies and synchrotrons. They are absolute sources in the sense that they produce outputs with calculable average radiance. But one cannot know when they emit individual photons. With the correlated-photon absolute source, by contrast, one knows not just the wavelength, direction and polarization of the individual photon, but also the momemt of its emission. The traditional sources require filters to pick out a specific wavelength. Overall, therefore, parametric down-conversion provides a new type of absolute source, very different from what we had before.

To implement such a new absolute optical source, one has to resolve four potentially problematic issues: First, because the efficiency of the trigger channel is less than perfect, there will be photons emitted from the source that go unannounced by the trigger. This problem can be addressed by implementing a fast optical gate that only allows photons through when the trigger says that one is coming. Second, any dark counts produced by the trigger channel would falsely indicate a photon output. But one can measure this small dark-count rate directly and use it as a subtractive correction.

Third, just as with trigger dark counts, any optical loss in the output path—for example, crystal absorption or reflection—would result in a trigger without an output photon. One can deal with such losses by measuring or calculating them, or designing minimal loss into the optical system so as to achieve the desired level of accuracy. (See box 2 on page 45.) Finally, if two pairs happen to be created close enough in time, one can have two source photons in conjunction with a single trigger. Because the electronic pulses in photon-counting systems typically have widths on the order of nanoseconds and most such systems operate at count rates below a megahertz, the probability of two emitted photons is small. It can be made arbitrarily small by reducing the rate of photon pair production even further.

The application described thus far applies to the calibration of photon-counting detectors. But that is not necessarily a fundamental restriction. Alexander Ser-

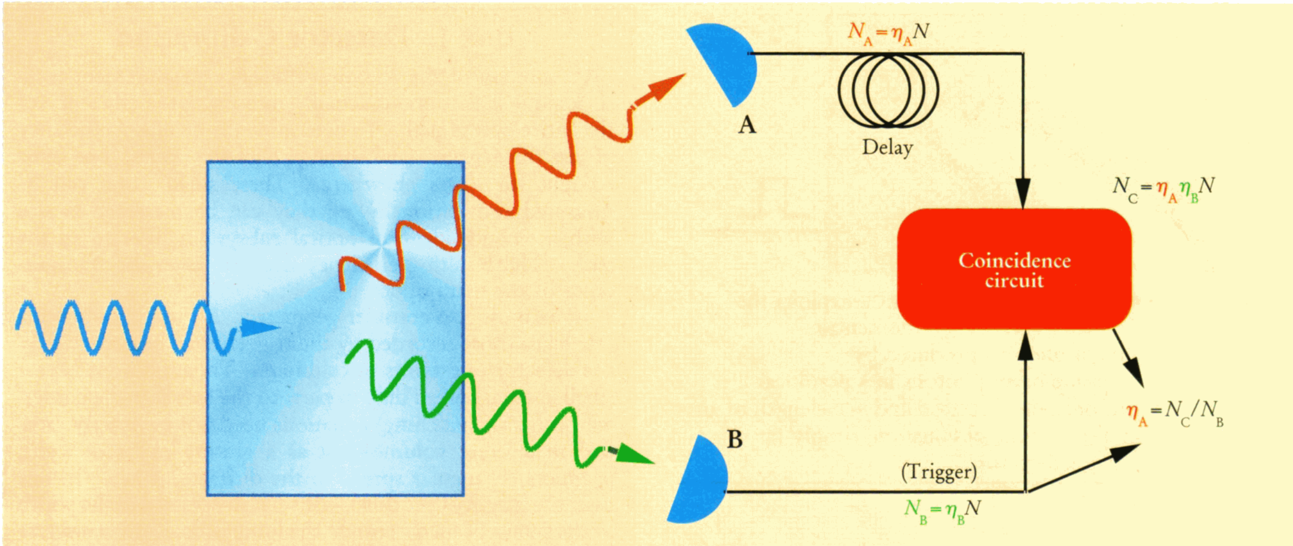

FIGURE 2. ABSOLUTE QUANTUM-EFFICIENCY DETERMINATION. N is the true number of correlated photon pairs produced in the down-conversion crystal, and N_A and N_B are the tallies of photons recorded individually by detectors A and B, with respective unknown efficiencies η_A and η_B. The number of expected coincidence counts N_C being N times the product of these two efficiencies, one arrives at the efficiency of A, the detector to be calibrated, without having to know the efficiency of B, the trigger detector.

gienko and Alexander Penin at Moscow State University demonstrated in 1986 that the technique can be extended to the calibration of analog detectors.[3] That is accomplished by replacing the coincidence circuit with an analog multiplier that correlates the identical Poisson-statistical variations in the two output channels. But because this correlation is proportional to the square root of the signal, such analog measurements become more difficult with increasing signal level. Here, for once, a higher *noise-to-signal* ratio is better.

Where is it useful?

The first demonstration of absolute calibration came with the first observation of the correlation between down-converted photons. But real metrological tests did not come until much later. The reported uncertainties[2,4-6] have improved over time from about 20% in 1970 down to 2% in recent years. But there were no truly independent tests of the method until the work of John Rarity's English group[7] in the late 1980s. They compared a conventional calibration of an avalanche photodiode with a correlated-photon measurement. Their conventional calibration was tied to an absolute scale by means of a photodiode power meter with an unstated uncertainty.

It was not until our work at the National Institute of Standards and Technology (NIST) in 1995 that an independent test of the method was made by comparing it with a conventional technique directly tied to a primary

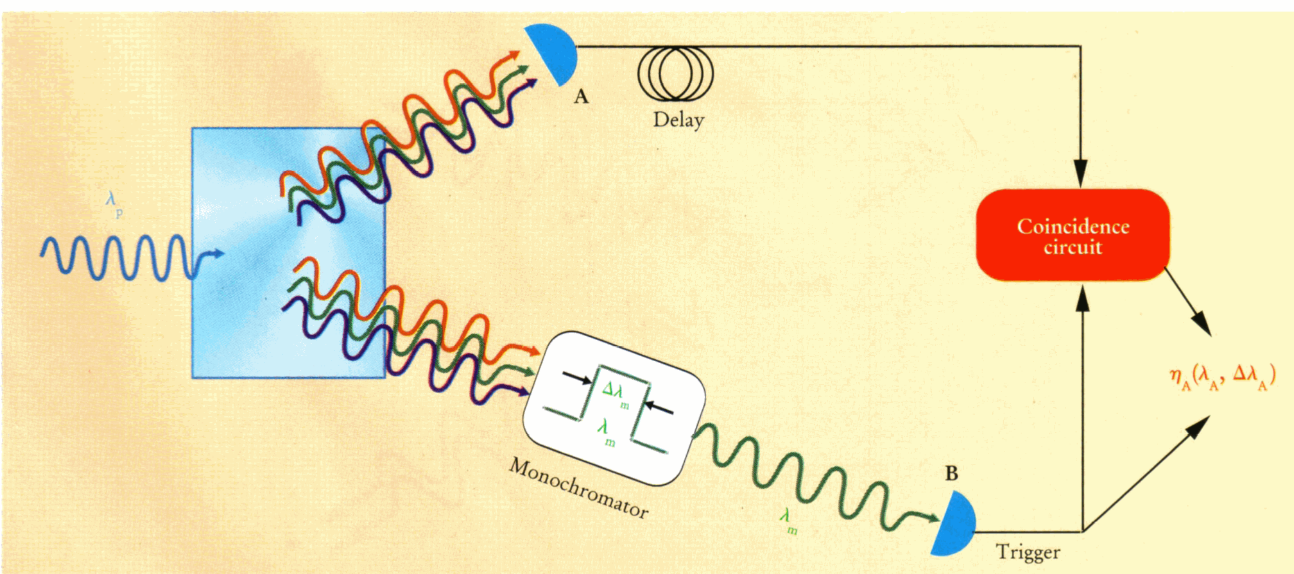

FIGURE 3. WAVELENGTH DEPENDENCE of the efficiency $\eta_A(\lambda_A, \Delta\lambda_A)$ of A, the detector to be calibrated, can be determined with the spectral filtering optics confined to the optical channel of B, the trigger detector. So it is not necessary to know the transmittance of the spectrally selective element. The frequency $\omega_A = 2\pi c/\lambda_A$ is given by ω_p, the pump-beam frequency minus ω_m, the center of the monochromator's passband $\Delta\lambda_m$.

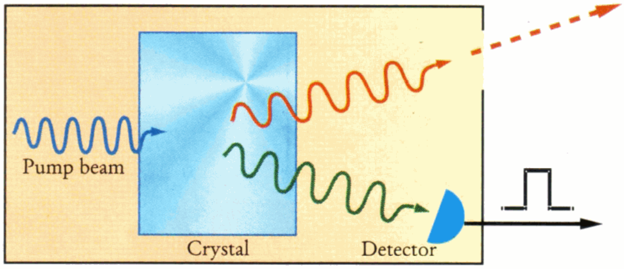

FIGURE 4. NEW ABSOLUTE PHOTON SOURCE exploits the constraints of simultaneity and energy–momentum conservation on pairs of photons produced by down-conversion of pump-beam photons in a nonlinear crystal to specify not only the direction and wavelength of an output photon, but also its time of emission, simply by recording its partner in a detector.

Box 1. Detector Calibration

A subtlety of the quantum-efficiency measurement technique is that one is actually measuring the efficiency of the entire optical path. To determine the quantum efficiency of just the detector (and some part of the optics), one must account for losses elsewhere. These small losses can be measured conventionally, or they can be measured *in situ* with a second, identical optical subsystem inserted in the path. The resulting efficiency decrease gives the transmittance of the extra optics.

One must also consider geometry. All the photons correlated to those recorded by the trigger must be collected by the detector one wants to calibrate. These photons have a small angular spread due, in part, to the fact that the conservation (phase matching) equations need not be exactly satisfied in a finite volume—just as a grating of finite width produces an angular spread in the diffracted beam. In our case, the length of the down-conversion crystal and the width of the pump beam determine the longitudinal and transverse spreading of the output beams.

standard.[8] This tight connection to a primary standard showed that the two methods agreed to within better than 2%. The average difference between the two methods, about 0.6%, is a plausible upper limit on any systematic bias of the new method. This initial comparison was most likely limited by the quantum-efficiency stability of the photomultiplier tube rather than the inherent limits of the method itself.

In the next round of tests of this method, we hope to push the systematic uncertainty down to 0.1% or better. Although this anticipated level of uncertainty would be just comparable to typical detector calibrations supplied by standards labs for the visible region, it would be a great improvement over typical infrared calibrations.

These absolute calibrations are most appropriate at the low end of the optical power range—typically less than a picowatt—where one usually does photon counting or low-level analog measurements. This complements nicely the present primary standards for optical detector calibrations: high-accuracy cryogenic electrical-substitution radiometers, which operate best at power levels of about 100 microwatts. At such relatively high power levels, one needs calibrated attenuators to reduce the signal to levels that can be handled by the photon counters. So, happily, the correlated-photon method works best in a regime where conventional measurement chains are the longest. Thus the two techniques can become independent primary standards at opposite ends of the dynamic range.

The absolute radiance method

The second metrological application of correlated photons we will discuss was proposed in 1977 by David Klyshko at Moscow State University[9] and demonstrated by Penin's

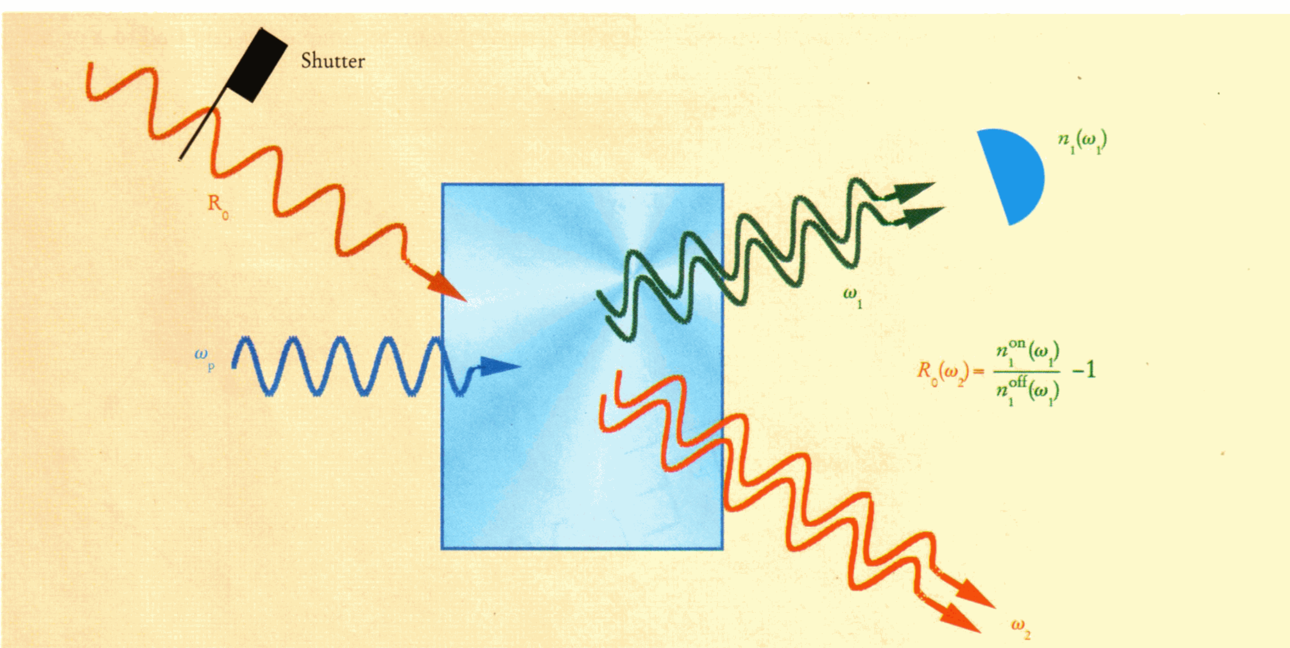

FIGURE 5. SPECTRAL RADIANCE of the photon beam R_0 can be measured at ω_2 by overlapping it with the crystal along the ω_2 output direction. The double wavy lines at output frequencies ω_1 and ω_2 indicate the enhancement of photon-pair production caused by adding the R_0 input. Enegy conservation dictates that $\omega_1 + \omega_2 = \omega_p$. If one measures the $n_1(\omega_1)$ signal with an uncalibrated detector in a convenient visible region, one can get the absolute radiance of R_0 in the more difficult infrared region ω_2 simply from the ratio of the visible detector signals with R_0 on and off.

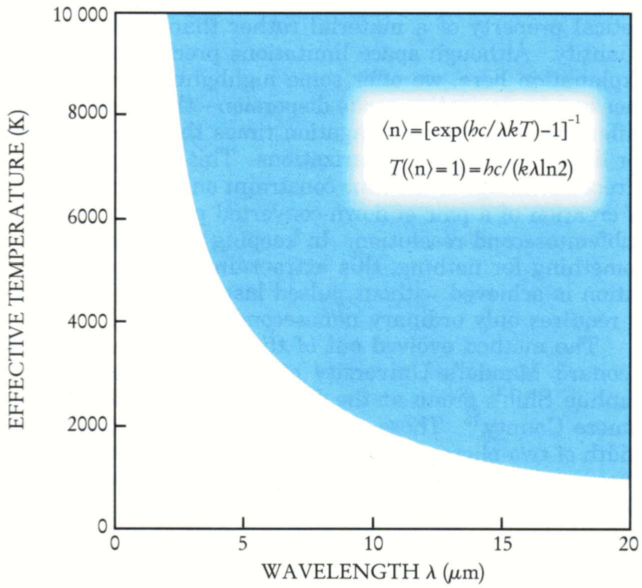

FIGURE 6. EQUIVALENT TEMPERATURE of a blackbody background with a spectral radiance of one photon per mode. Formulas are displayed for the mean number of photons per mode at a given wavelength and temperature as well as for the temperature required for a source to emit, on average, one photon per mode at the given wavelength. (k is Boltzmann's constant.) The blue region above the curve indicates the regime of wavelengths and temperatures best suited for absolute radiance measurement with correlated photon pairs.

group two years later.[10] This application provides a means of determining the spectral radiance of an optical source in an absolute manner, again without relying on any previously calibrated device. As a bonus, it allows infrared radiance to be measured with visible detectors and optics.

The basic measuring arrangement is that of an optical parametric amplifier, as shown in figure 5. Starting with the spontaneous down-conversion geometry of figure 1 (one photon in, two photons out), the radiance beam to be measured (R_0) is directed into the crystal so as to overlap both spatially and spectrally with some of the spontaneously down-converted output. This arrangement enhances, or stimulates, decay of the pump beam into the down-converted channel. However, because all the output photons must be created in pairs, the output light along the other channel is also stimulated. So one can monitor, at one wavelength, the level of an input beam at a different wavelength. Thus, it becomes possible to monitor infrared beams with stable, high-quality visible detectors.

This simple monitoring is then turned into an absolute measurement of spectral radiance by considering the origin of the down-converted light produced when the beam to be measured is blocked—that is to say, when only the pump beam is incident on the crystal. This spontaneous decay of pump photons can be thought of as being stimulated by a one-photon-per-mode background due to zero-point vacuum field fluctuations[1] and radiation reaction.[11] It turns out that this one-photon-per-mode radiance can be written in terms of the wavelength λ and fundamental constants as hc^2/λ^5, which has the right units, namely power per unit area and bandwidth.

The absolute spectral radiance of an unknown beam can then be determined by observing the signal increase in channel 1 as the unknown beam is put into the crystal to overlap channel 2. The ratio of the increase in the output signal to the spontaneous signal is the radiance of the unknown beam, in units of photons per mode. The detector needs no calibration; its only requirement is linearity. The spectral band of the radiance measurement is the range of wavelengths correlated to those seen by the detector in channel 1. In effect, this method allows an unknown beam to be compared to an absolute standard that exists everywhere and is available to everyone. From a metrological view, such an "omnipresent standard" is the ideal primary standard.

As with the absolute quantum-efficiency technique, there are real-world effects to be considered. In this case, there are two important effects: The first and simplest is that the radiance measured is the radiance *within* the down-conversion crystal. So, to extract the radiance of a specific source, one must account for any transmittance losses in imaging the source radiance into the crystal. The second effect involves how well the radiation to be measured fills the field modes to which this technique is sensitive. This filling is ultimately described by an overlap factor. The trick is to design the system with as large an overlap factor as possible. Note that it is not necessary to know how *many* modes are filled, only how well they are filled by the unknown beam. For details, see box 2.

Penin's Moscow group first demonstrated this method[10] by looking at three different sources: a laser, a fluorescent dye pumped by a laser, and an incandescent lamp. They measured out to a wavelength of 3.9 μm in the infrared with a photomultiplier tube and spectrometer designed for observations in the visible. This achievement highlights the technique's ability to exploit convenient visible components for more difficult infrared regions.

The effective temperatures of the sources and the wavelengths at which they were measured (500 000 K and 70 000 K at 532 nm and 980 K at 3.9 μm) in the original work of Penin's group indicates the range over which this method is most appropriate. Because the background standard is one photon per mode at all wavelengths, the most accurate comparisons will be achieved when one is measuring sources with similar or larger radiances—so that the increase in signal will be sizable relative to the one-photon-per-mode background.

Figure 6 shows the equivalent temperature of a source with a spectral radiance of one photon per mode as a function of wavelength, with temperatures ranging from 10 000 K at 2 μm to 1000 K at 20 μm. The technique

Box 2. Spectral Radiance

To correctly extract the spectral radiance of the source from the down-converter output ratio, one needs to know two factors: (1) a straightforward factor due to infrared input losses, and (2) a more complicated factor that quantifies the overlap between the infrared input beam and the crystal region that produces down-converted light of a particular wavelength. This region has an approximately Gaussian transverse profile. Ideally, it would be uniformly bathed in the light of the infrared beam to be measured.

One might expect to approach this ideal simply by expanding the beam. Unfortunately the *angular* spread of the interaction region (due here, in part, to the variation of output angle with wavelength) must also be maximally filled. As a result, one cannot simultaneously maximize both the angular and spatial overlaps. Recent modeling of these overlap factors by our group[17] finds an optimum magnification that maximizes the product of the two factors and brings the overlap close to the desired ideal. These model calculations appear to agree well with experimental results.

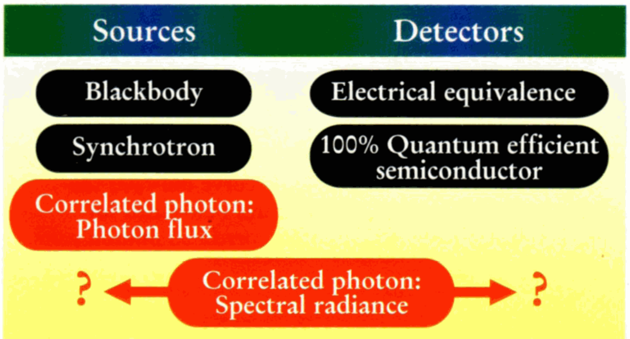

FIGURE 7. ABSOLUTE RADIOMETRIC STANDARDS. The new ones that use correlated photon pairs are shown in red. Electrical-equivalence detectors, with a radiation absorber in contact with an electrical heater and a temperature sensor, measure radiant power relative to electrical power. Some semiconductor detector arrangements, with quantum efficiencies close to 100%, serve as absolute standards. Both detector types use optical trap configurations to reduce reflective losses. The new spectral-radiance arrangement can be regarded either as an absolute source or an absolute detector.

will be most suitable for measuring sources in the high-temperature, infrared region above the curve in the figure. But that is not a stringent limit. Because the measurement is comparing the spontaneous signal to the additional down-converted signal due to the unknown beam, the method is limited by how well one can determine this difference.

Once again, a true test of the method requires independent verification of its accuracy. Such a comparison was recently performed in our lab at NIST, with a high-temperature discharge arc that had previously been independently calibrated against a blackbody.[12] We measured spectral radiance out to nearly 5 μm with a silicon detector operating in the visible. That comparison, along with recent refinements,[13] found that the old and new methods agreed to within better than 2%.

So we see that entangled photon pairs not only provide an absolute method to measure spectral radiance without a calibrated detector; they also allow us to measure infrared radiance without even an infrared detector. Furthermore, this method gives us a new type of absolute spectral-radiance source. That's truly a rare find.

It is useful to point out how the two applications discussed above fit into the world of absolute radiometric standards—that is to say, standards whose output or response can be calculated from fundamental physical principles. In the figure 7, the existing absolute sources and detectors are shown in black. Because there are so few, any addition can have a significant impact. The correlated-photon absolute flux source clearly fits in the first column in the figure. The placement of the correlated-photon spectral radiance method is not so clear. As a technique for measuring spectral radiance, it can be regarded as an absolute detector. But alternatively, it is also simply a way of coupling to an omnipresent absolute spectral-radiance source—the one-photon-per-mode vacuum background—by means of the energy- and momentum-conservation constraints. In either case, the table makes it clear that correlated photons offer significant new choices in the world of radiometry.

Polarization mode dispersion.

Progress has also been made on a third metrological application of correlated photons, which differs from the applications we've been discussing in that it measures an optical property of a material rather than a radiometric quantity. Although space limitations preclude a detailed explanation here, we offer some highlights: The method measures polarization-mode dispersion—that is to say, the difference in optical propagation times through a sample for light of orthogonal polarizations. This technique takes direct advantage of the time constraint on the simultaneity of creation of a pair of down-converted photons. It yields subfemtosecond resolution. In keeping with the theme of something for nothing, this extraordinary temporal resolution is achieved without pulsed lasers of any kind, and it requires only ordinary nanosecond electronics.

The method evolved out of the fundamental work of Leonard Mandel's University of Rochester group,[14] and Yanhua Shih's group at the University of Maryland Baltimore County.[15] These groups measured the shape and width of two-photon wavefunctions by means of a nonlocal quantum-interference effect, thus showing that polarization-mode dispersion could be determined with femtosecond resolution. More recent work in our laboratory[16] has demonstrated 150-attosecond (1.5×10^{-16} s) resolution. This approaches the Heisenberg uncertainty limit on the simultaneity of photon pair creation. New schemes may allow us to surpass even this limit, because the uncertainty principle only sets a lower limit on the spread of the temporal distribution, not on how well we can know its mean. Stay tuned for more amazing results from two-photon metrology.

In this article, we have highlighted the metrological potential of two-photon states. We hope it will spur others to explore the possibilities. Each of the applications exhibits unusual characteristics: absolute measurements with uncalibrated detectors, infrared measurement without infrared detectors and subfemtosecond timing that pushes the uncertainty principle. These possibilities all have their origin in the weirdness of the entangled two-photon state. Because these fundamentally dual creatures are so far outside of our intuition, it is likely that other interesting applications are yet to be discovered.

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