

several millimetres and deflect them up to some 18° off the main beam direction. The intensity distribution was measured as a function of the exit angle with a pixel detector. The images show a characteristic peak corresponding to the guided beam alongside a weaker horizontal ‘streak’ towards lower angles. The streak, extending in the direction parallel to the plane of the waveguide chip, is a signature of optical power leakage, that is, intensity tunnelling off the waveguide and escaping through the tantalum walls.

To investigate the nature of the diffracted intensity in closer detail, the group performed a second experiment. This time they used the European Synchrotron ESRF and a higher-resolution pixel detector to investigate the fine structure of the spatial distribution of the far-field intensity as a function of the exit angle. With the second experiment, the group unequivocally showed that the streak intensity originated from leaky modes. The leaky modes intensity is not constant over the angular range, but in fact depends on which modes contribute to the intensity tunnelling at any position and on their interference.

Higher-order modes tend to have higher attenuation and leak out faster than lower-order modes. Their experimental data confirm this prediction. During the same experiment, the group demonstrated that X-rays can be bent up to about 30° from the main beam direction.

The curved waveguides of Salditt *et al.* are uncapped, guiding X-rays in the horizontal dimension only, and that increased radiation decoupling from the open top. Transmission efficiency is an issue with such small (100 nm) channels, and Salditt and co-workers addressed the problem by using pre-focusing optical elements to couple X-rays into the waveguides.

While some work is still required to improve on the overall efficiency, the experimental demonstration of Salditt and colleagues already constitutes a serious step forward towards the realization of X-ray photonics devices. Handling the curvature of the X-ray channels allows for an increased versatility of use, to implement delay lines, micro-interferometric set-ups, or beam splitting and merging over two or multiple channels.

Innovative X-ray femtosecond pulsed sources<sup>12–14</sup> now becoming available will require novel X-ray optics able to manipulate both the spatial and spectral properties of intense X-ray pulses. X-ray waveguides may constitute examples of such devices<sup>15</sup>, following the very development that brought optical waveguides to be the basic building blocks of photonic circuits. □

Daniele Pelliccia is at the School of Science, RMIT University, GPO Box 2476, Melbourne, Victoria 3001, Australia.

e-mail: [daniele.pelliccia@rmit.edu.au](mailto:daniele.pelliccia@rmit.edu.au)

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## QUANTUM OPTICS

# Spooky spectroscopy

The quantum concepts of entanglement and interaction-free measurements are applied to spectroscopy to successfully sense carbon dioxide in air.

Jean-Pierre Wolf and Yaron Silberberg

**Q**uantum metrology is blooming in a wide range of applications including telecommunications, microscopy, and spectroscopy. For example, take quantum coherent control<sup>1</sup> — a concept where custom-designed light fields are used to transform a quantum system from one state to another. It is already well established that the approach can identify different molecules that exhibit nearly identical absorption and fluorescence spectra, a situation that would defeat conventional optical spectroscopy.

In 2009, quantum coherent control was successfully performed on vitamins to discriminate between riboflavin and flavin mononucleotide<sup>2</sup>. In this experiment, the optimally tailored phase and amplitude of the laser field is transferred to the sample via dipole interaction, and the interference between the different excited states

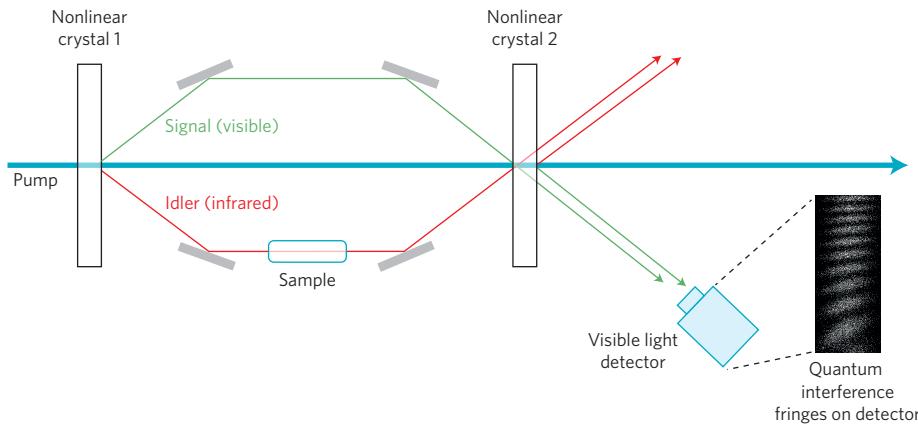
generates a matter wave packet that evolves with time. Since quantum interferences are sensitive to subtle differences in phase between the excited states, the matter wave packets of the two molecules exhibit significant differences, which can be exploited for the discrimination of their respective fluorescence signals. This method found immediate application in microscopy and biology. More recently, quantum control-based discrimination has been applied to different types of peptide and amino acid<sup>3,4</sup>.

Now, quantum sensing and spectroscopy has taken another step forward with the report that photon entanglement, a quintessential quantum property, can be harnessed to identify traces of a particular molecule in an ensemble of background molecules. Writing in *Nature Photonics*, Dmitry Kalashnikov *et al.*<sup>5</sup> report the use

of pairs of entangled photons, one visible and one infrared, to measure selectively the concentration of CO<sub>2</sub> in the air.

The approach adopts the quantum concept of ‘interaction-free measurements’ to determine the sample’s properties without actually measuring the photons that interacted with the said material. This interaction-free paradigm was recently demonstrated with quantum imaging<sup>6</sup>, where the infrared (1.55 μm) photons from the entangled pairs were transmitted through an object but not detected, while the visible signal photons were detected and provided information on the object shape.

Kalashnikov *et al.* have now extended this strategy to spectroscopy. They sense and identify the presence of CO<sub>2</sub> in the atmosphere, via its infrared absorption spectrum, without actually detecting the



**Figure 1 |** Spooky spectroscopy. To measure the sample's infrared absorption, a photon from the visible pump beam is split into a visible 'signal' photon and an infrared 'idler' photon by a nonlinear crystal. The infrared idler photon interacts with the sample. The two photons then cross a second crystal, where another photon pair can be generated. By measuring the visible signal photons (which never passed through the sample) one can detect the infrared properties of the sample. Image of quantum interference fringes adapted from ref. 5, Nature Publishing Group.

infrared light that has passed through the sample.

Beyond being a clever quantum trick, the approach could be important as visible light detectors are considerably more sensitive than infrared detectors and hence this technique could be extended to improve spectroscopy in spectral regions where good detectors do not currently exist.

To get some insight into how this approach works, consider the schematic set-up in Fig. 1. The main components of the experiment are two identical nonlinear crystals separated by some distance, where the sample under test is placed. A visible laser beam (the 'pump') crosses the set-up and its interaction with the nonlinear crystals leads to the probabilistic formation of entangled photon pairs through the process of spontaneous parametric down-conversion — a 'pump' photon occasionally splits into two photons, the 'signal' and the 'idler', whose frequencies sum up to the pump frequency (as dictated by conservation of energy). The values of these two frequencies can be set by the choice and orientation of the crystal, here one is tuned to the infrared, and the other is visible.

The key point is that when detecting a photon from the entangled pair (in this case with a visible light detector), it is impossible to know in which crystal it was created — and quantum mechanics tells us that two such indistinguishable events interfere. This is not very different from the archetypal quantum two-slit experiment, where there is no way to tell through which slit a particle has passed, only that here in each event two photons are created. The phase that determines this interference

signal at the detector depends on the optical phase of all three photons (pump, signal and idler) as they travel between the crystals, leading to oscillations in the probability to detect the event. As the sample affects the transmission or the phase of the infrared photon, it also affects the rate of detection of its visible partner.

These ideas, that it is not the photons that interfere but the indistinguishable events, can be traced back to key ideas of a pioneer of quantum optics Leonard Mandel<sup>7,8</sup>. The concept was recently beautifully exploited by the group of Anton Zeilinger for imaging with undetected photons<sup>6</sup>. It is closely related to another quantum trick known as interaction-free measurement, where objects can be detected by light, even when no photon hits them<sup>9</sup>. What looks at first like another spooky aspect of quantum physics can actually be useful for the practical down-to-earth task of spectroscopy of a trace substance.

In addition to the advantage of detecting visible photons instead of infrared ones, Kalashnikov's quantum sensing set-up could potentially be the basis for a new breed of compact, portable and energy-efficient sensing equipment that does away with the need for cooled detectors. Possible applications could range from trace gas detection in the atmosphere, exhaled air analysis from patients for diagnostics purposes, flow cytometry and microfluidics analysis, and chemically specific imaging in the fingerprint region if the sample in the idler beam can be spatially scanned. An additional advantage would be, in this latter case, that the infrared photons would

be much less efficiently scattered by the medium than their visible counterpart.

However, for demanding applications requiring maximum sensitivity, further improvements would be required to lower the system's detection limit. This could be achieved by increasing the production rate of entangled photon pairs, provided that each pair is distinct from its predecessor, or by extending the absorption path length using multi-pass cells. After all, it should be noted that entanglement has recently proven to be surprisingly robust and remains intact over 140 km of open path through the atmosphere<sup>10</sup>.

One interesting question that arises, then, is how many photon pairs can one generate and still claim that they arrive 'one by one' (or rather 'pair by pair') and thus retain their quantum properties? It turns out that the number can be quite high. The time slot each pair occupies is related inversely to its spectral bandwidth, and so to cram a lot of pairs into a channel one would want to generate them so that they are as spectrally broad as possible. Other experiments have reported that fluxes of  $10^{12}$  pairs per second are achievable<sup>11</sup>. Yet, is it really necessary for the pairs to arrive one by one? What happens if the rate will get even higher and the simple quantum picture outlined above no longer holds? While Kalashnikov *et al.* have not discussed this issue<sup>5</sup>, it is an important point to consider, since this is the route to get stronger signals and a better signal-to-noise ratio. Looking at Fig. 1 from a classical point of view, each of the crystals is now a parametric amplifier — which may amplify or attenuate the incoming signal and idler beams, depending on their relative phase. So while the first crystal has no input, and it amplifies noise to generate the signal and idler beams, the second crystal amplifies (or attenuates) these beams, and whether it amplifies or attenuates them depends on the phase they (and the pump) acquired between the two crystals. Hence, modulation of the idler phase and amplitude that is introduced by the sample can still be detected via measurements of the visible signal beam alone.

The fact that spooky quantum properties are maintained at stronger 'classical' intensities should actually not be surprising. We observe Young's interference fringes even at high intensities; there is no need to send those photons one by one. Similarly, quantum imaging can be extended to higher intensities<sup>12</sup>. Yet, as many quantum experimentalists know, inspiration from quantum physics can often lead to applications in mundane (yet practical) classical optics. □

Jean-Pierre Wolf is at the Group of Applied Physics, University of Geneva, 22 Chemin de Pinchat, 1211 Geneve 4, Switzerland. Yaron Silberberg is in the Department of Physics and Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel.  
e-mail: [Jean-Pierre.Wolf@unige.ch](mailto:Jean-Pierre.Wolf@unige.ch); [yaron.silberberg@weizmann.ac.il](mailto:yaron.silberberg@weizmann.ac.il)

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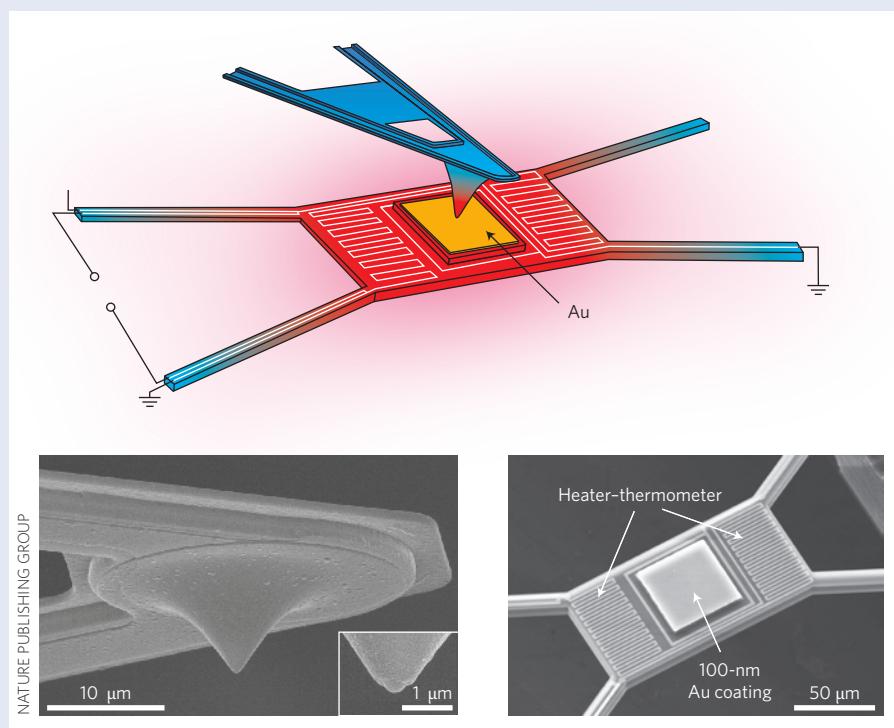
## INFRARED OPTICS

# Nanoscale heat

Radiative heat transfer via the emission of light, which largely involves photons at infrared wavelengths, is a well-known phenomenon taught in undergraduate physics courses. Yet, the effect is still not fully understood when it occurs on the nanoscale. Studies have shown that the rate of thermal radiation by light can be modified by altering the optical properties of structures and can dramatically deviate away from the values expected from conventional black-body physics. In particular, enhanced heat transfer has been achieved via structures such as diffraction gratings and small gaps between surfaces supporting modes at infrared wavelengths. Unfortunately, it is difficult to quantify the effects for gaps smaller than a few tens of nanometres. And, not all of the theoretical studies on nanoscale heat transfer are in agreement.

Kyeongtae Kim, Bai Song, Víctor Fernández-Hurtado and colleagues from the USA, Spain and South Korea have now experimentally demonstrated a technique to measure radiative heat transfer for gaps as small as 2 nm using custom probes with embedded thermocouples (*Nature* **528**, 387–391; 2015).

One of the authors of the study, Pramod Reddy, told *Nature Photonics* that the motivation of this work was to elucidate the principles governing the exchange of thermal radiation between objects separated by gaps as small as a few nanometres and to establish the basic laws that can be applied to a great variety of nanoscale systems and devices. Reddy explained that one of the most important findings is the unambiguous demonstration that the theory of fluctuational electrodynamics provides an accurate description of the radiative heat transfer all



the way down to separations of a few nanometres.

According to Reddy, it was a real challenge to measure the very small heat flux between the gold surfaces in their experiment, which was beyond the sensitivity of existent techniques. "This required the combination of our scanning probes with microdevices capable of periodic temperature modulations, which led to an increase in resolution by more than an order of magnitude. This improvement was crucial to establish a definitive picture of the radiative heat transfer between metals at the nanoscale," Reddy explained.

"Our results demonstrated that in nanometre-scale gaps the radiative heat

fluxes can be many orders of magnitude larger than what is expected from the Stefan-Boltzmann law for black bodies," Reddy told *Nature Photonics*. "This discovery can be extremely useful for technologies that make use of thermal radiation such as thermophotovoltaics, heat-assisted magnetic recording or nanolithography."

The team now hopes to use their findings to tackle a variety of open problems such as the active control of thermal radiation in nanoscale devices and applying nanostructuring to shape the spectral characteristics of thermal emissions.

DAVID PILE