OPTICAL SPECTROSCOPY

Clever calibration

A spectroscopic method that combines the accuracy of optical frequency combs with the rapid tuning of an external-cavity diode laser opens the door to fast, broadband spectral characterization.

Thomas R. Schibli

Rapid, wide-band spectroscopy may benefit greatly from a new technique that provides simple, on-the-fly calibration of a rapidly scanning external-cavity laser diode. It allows for sub-megahertz precision optical spectroscopy in an easy-to-use set-up, and significantly broadens the horizon for precision optical spectroscopy of rapidly evolving or drifting systems. The scheme is reported on page 529 of this issue by researchers in Germany and Switzerland[1].

Since the initial observation of mysterious dark lines in the solar spectrum by Fraunhofer in 1814, researchers around the world have used precision spectroscopy to investigate the inner workings of matter. Fraunhofer's research was followed by Kirchhoff, Bunsen and others, and by 1870 spectroscopy had advanced to become a powerful tool for chemical gas analysis. Each element and molecule shows a distinct spectral absorption 'fingerprint', and this is used by chemists to analyse the chemical composition of unknown substances. Even today, spectroscopy remains the only method to identify the chemical composition of distant stars and interstellar matter.

Spectroscopic methods improved significantly after the invention of the laser in the late 1950s, but it was not until the late 1990s that the discovery of laser frequency combs (honoured with the 2005 Nobel Prize for Physics[2]) finally led to a true revolution in the field of precision measurement. Development continues apace and there is still a need for spectroscopic tools with even better precision — for example, in measuring the lamb-shift of the atomic ground state (predicted by quantum electrodynamics) and in the on-going debate about the constancy of physical constants.

As a result of this rapid development, the complexity of the 'tools of the trade' is making it increasingly difficult to use the latest advances in practical applications. On page 529 of this issue, Pascal Del'Haye and co-workers introduce a radically simplified, yet very effective way to incorporate state-of-the-art optical frequency comb technology into a simple-to-use precision spectroscopy set-up. Furthermore, this new technique allows for very fast scanning speeds (~1 THz s^{-1}) with sub-megahertz resolution over large spectral bandwidths (>4 THz) in the 1,550-nm range, allowing precise measurements in rapidly evolving systems.

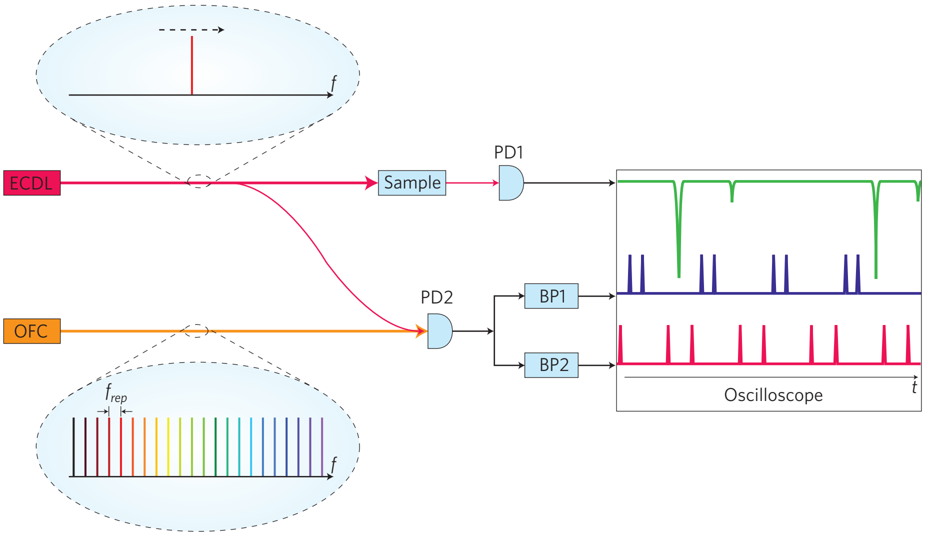

Figure 1 | Spectroscopy with an on-the-fly calibrated extended-cavity diode laser (ECDL). The light of a rapidly scanning ECDL is sent through the sample, where it is attenuated to reveal the sample's spectroscopic signature. A fraction of the ECDL light is made to interfere with a stabilized optical frequency comb (OFC). The detected beat notes are then sent through two band-pass filters (BP1 and BP2) and recorded on a multi-channel oscilloscope together with the spectroscopic signal. This leads to distinct calibration markers (blue and red) alongside the spectroscopic data (green). PD, photodetector; f_{rep}, pulse repetition rate of the optical frequency comb.

The reported set-up is based on a commercially available frequency comb, a rapidly scanning single-mode external-cavity diode laser (ECDL) and two radio frequency (RF) band-pass filters (Fig. 1). The method is innovative because the ECDL is free-running, and instead of being stabilized to the frequency comb, its frequency is only monitored. The light of the ECDL is split into two, with one part sent to the sample — the device being tested — and the second used to interfere with the frequency comb. The interference is detected by a photodiode (PD2) and the resulting photocurrent contains a set of RF beat notes that represent the frequency difference between the ECDL and the nearest comb lines of the frequency comb. This RF signal is then split and fed through two megahertz-wide RF band-pass filters (BP1 and BP2) to generate a set of reference frequency 'tick marks'. A multi-channel oscilloscope records these tick marks and the spectroscopic signature of the sample. The two central frequencies of the RF band-pass filters are chosen to be one fifth and two fifths of the spacing of the frequency comb (or one third, if only one filter is used) to achieve uniform spacing of the tick marks. Any position between these tick marks can be accurately determined using spline interpolation, and Del'Haye *et al.* report an accuracy in their first set-up of ~1 MHz, at a scanning speed of 1 THz s^{-1}.

Of course, the simplicity and the high speed of this new approach introduce a few limitations. Most importantly, there is a direct trade-off between the scanning speed and achievable spectral resolution. Causality dictates that the resolution of this method is limited to scanning speeds of the order of the square of the narrowest features to be resolved. Thus, if one desires to resolve 1 MHz-wide features, the scanning speed will be limited to ~1 THz s^{-1}. This limitation can only be circumvented by the use of broadband techniques, in which all colours are interrogated simultaneously. However, broadband techniques usually have their own trade-off between limited resolution and limited spectral coverage[3–6].

At very low scanning speeds, the scheme developed by Del'Haye *et al.* is limited by the free-running linewidth, as well as the low-frequency jitter of the tunable laser, owing to the fairly large spacing of the calibration markers (tens of megahertz). This lower scanning speed limit also imposes a limit on the dynamic range that can be achieved, as a result of the limited interrogation time. By averaging multiple rapid scans, it is possible to improve the dynamic range at the cost of measurement times that are longer when compared with coherent measurements. Therefore, this method is particularly well suited for samples with reasonably strong spectroscopic features (>0.1% absorption) that are wider than the square root of the ECDL scanning speed.

To demonstrate the effectiveness of the first implementation of this technique, Del'Haye *et al.* measure the dispersion of a toroidal microresonator — small silica toroids on a silicon chip[7]. Such resonators boast optical quality factors in excess of 100 million. It was previously reported by the same authors that cascaded four-wave mixing inside such resonators can lead to the generation of optical frequency combs[8]. The effectiveness of this process relies not only on high optical quality factors and small mode-volumes, but also on a uniform spacing of the cavity resonances; that is, they require cavity dispersion to be small. Owing to the very large free spectral range of such cavities (~0.1–1 THz), previous broadband methods[9] cannot be adapted for measurement of their dispersion. So far, the dispersion of such small resonators was only known from theoretical finite-element and analytical calculations. The method presented by Del'Haye and co-workers now allows for a direct measurement of the non-uniformity of the free spectral range of these cavities, and hence for the cavity dispersion. The results obtained match the theoretical calculations beautifully[1].

As a result of the decreased frequency resolution, on-the-fly calibration of a rapidly scanning ECDL will probably not replace phase-locked systems currently at the forefront of precision metrology. However, there are undoubtedly countless applications — especially those involving drifting spectral behaviour — that will benefit from rapid data acquisition more than the ability to obtain extreme resolution. ❐

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NANOPHOTONICS

Probing near-field thermal radiation

New insights into the behaviour of radiative heat transfer at the nanoscale have now been made, thanks to highly precise measurements made using scanning probe microscopy.

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In 1900, Max Planck used quantum theory to explain the puzzling nature of the spectral density of thermal far-field radiation. Since then, the behaviour of far-field thermal radiation has been considered a reasonably well-understood phenomenon. However, Planck realized that the situation becomes more complex in the near-field regime, where the distance between two bodies is comparable to the characteristic wavelength of thermal radiation (that is, the sub-micrometre range).

According to current theory, the contribution of evanescent modes (near-field modes that decay exponentially with distance; Fig. 1) to total heat transfer increases rapidly and approaches infinity as the distance between the surfaces approaches zero, allowing evanescent heat transfer to dominate at the nanoscale.

These evanescent modes originate mainly from surface plasmon-polaritons in the case of metals, and surface phonon-polaritons in the case of non-metals. The physical mechanisms and phenomena occurring in this nanoscale region have received significant attention in the last decade because of improvements in nanostructure fabrication, the development of advanced scanning probe microscopy and interest in basic research. The findings are having an influential role in new concepts such as thermophotovoltaics, nano-electromechanical systems, heat-assisted magnetic recording, heat-assisted lithography, the design of devices that rely on resonant or coherent heat emission, and nano-antennas.

On page 514 of this issue[1], Emmanuel Rousseau and co-workers report results obtained with a new experimental set-up that allows highly precise measurement of heat transfer over a small gap between a heated, flat surface and a micrometre-scale sphere mounted on the bimorph cantilever of an atomic force microscope. Importantly, their experiment confirms that the so-called 'Derjaguin approximation', also known as the 'proximity-force approximation', is valid.

Heat transfer across the plate–sphere gap causes the cantilever to bend very slightly, and this is measured by optical fibre interferometry (Fig. 2). The set-up is operated under a closed-loop control scheme, which keeps the parasitic heat transfer entering the cantilever constant and thus improves the accuracy of measurements.

This stabilization is achieved by regulating the output power of the