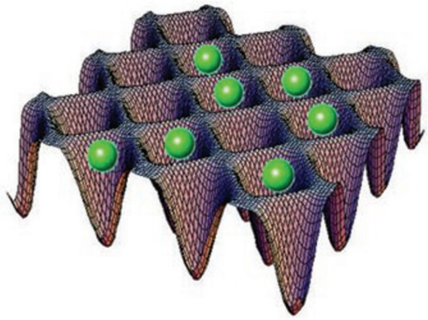
The next step for metrology

Frequency combs, optical clocks and quantum techniques that go beyond classical limits are all making photonics a powerful tool for understanding and defining our universe in ever-greater detail.

This issue of *Nature Photonics* has a special focus on next-generation metrology, featuring a collection of three Reviews, two Commentaries and an Interview all dedicated to the topic. Light has played a key role in metrology since 1960, when the metre was defined by the number of vacuum wavelengths of a particular spectral line of ^{86}Kr (ref. 1). More recently, optical metrology has not only seen significant improvements in precision for such tasks[2], but has also greatly extended its use to size measurements of subatomic particles[3]. Two of the most useful tools developed within this field so far are perhaps the optical frequency comb — a periodic set of spectral lines that are equally spaced in the frequency domain — and the optical clock, which makes use of a stabilized ultranarrow radiative atomic transition. Both tools have significantly improved our ability to make precise measurements of frequency and time.

On page 193 we have an interview with Theodor Hänsch, director of the Max Planck Institute for Quantum Optics and a 2005 Nobel laureate in Physics for "contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique." Hänsch remarks on the great impact that frequency combs are having in many areas of science, particularly for Fourier spectrometers, which have seen dramatic improvements in resolution and recording speed over recent years. Hänsch explains that such improvements may reveal new insights into the expansion rate of the universe or the nature of fundamental physical constants. Just last year, the frequency comb enabled the size of the proton to be measured at record-accuracy using the Lamb frequency shift[3]. Hänsch's own laboratory is now working towards miniaturizing the optical frequency comb system by using toroid-shaped optical microresonators, with the aim of making the technology cheaper and easier to deploy.

In a Commentary on page 186, Nathan Newbury from the National Institute of Standards and Technology in Colorado, USA, explains that there are a myriad of applications for optical frequency combs. In the field of astronomical spectroscopy, optical frequency combs can provide



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the performance necessary to measure changes in the cosmological red-shift or the extremely small Doppler shifts resulting from planets orbiting distant stars. Newbury says the phase coherence and broad optical bandwidths of frequency combs can also be exploited for frequency transfer and timing synchronization across optical fibre networks, and explains that modulating a frequency comb with a specific phase and amplitude enables the generation of arbitrary optical waveforms.

Another topic that has received great interest within the field of optical metrology is the development of optical clocks for improved temporal standards. The current definition of the second, as decided in 1967, is the duration of 9,192,631,770 periods of the radiation emitted between two hyperfine levels of the ground state of the ^{133}Cs atom[4]. However, the stability of single-ion-based optical clocks is limited by quantum projection noise.

In a Review on page 203, Hidetoshi Katori summarizes progress in the development of optical lattice clocks and their role in quantum metrology. Optical lattice clocks are composed of ~10^6 neutral atoms trapped in a lattice pattern formed by interfering laser beams. In this system, unwanted Doppler and collisional shifts in the radiative transition under study can be suppressed. The key point to realizing an optical lattice clock is finding the 'magic wavelength' that enables strong spatial confinement of the atoms with no impact on the clock transition frequency. As well as describing the principles of the optical lattice clock, Katori discusses prospects for improving accuracies beyond the Dick limit — currently the precision limit for optical lattice clocks. In a Commentary on page 189, Rick Trebino describes techniques for characterizing ultrashort optical pulses based on the use of frequency-resolved optical grating and holography. Such schemes now make it possible to collect the intensity and phase information of a pulse in a single-shot measurement.

Classical measurements are limited by statistical and systematic errors. Statistical errors, originating either from insufficient control of the measurement system or from physical limits such as the Heisenberg uncertainty principle, can be reduced by repeating the measurement n times and then averaging the outcomes. This process converges to a Gaussian distribution with a standard deviation that scales as $n^{-1/2}$. However, using quantum effects such as entanglement and squeezing makes it possible to improve measurement precision beyond this level, decreasing the error by an amount proportional to n^{-1}. In a Review on page 222, Vittorio Giovannetti *et al.* describe the theory and prospects of quantum metrology, a field that provides advantages in precision over purely classical approaches.

Optical metrology is also being used to measure ultraweak forces, which is a growing requirement in the field of nanotechnology. One challenge in particular is the measurement of the Casimir interaction, a submicrometre-scale force induced by quantum fluctuations of the electromagnetic field between two neutral bodies. Over the past ten years, dramatic progress has been made in the theoretical understanding and measurement of the Casimir force. New computational methods now allow us to analyse the Casimir force between both planar and non-planar geometries. In a Review on page 211, Alejandro Rodriguez *et al.* describe the basic physics of the Casimir interaction, summarize recent experimental systems and outline theoretical progress together with some of the latest predictions regarding this unusual force. ❐

References

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