

Unprecedented precision in the synthesis and division of optical frequencies

High-resolution spectroscopy of atoms and molecules has been, and continues to be an essential experimental tool in the formulation and development of quantum mechanics, the measurement of atomic properties, the determination of fundamental constants, and in the realization of standards for time and length. Not only are we able to directly probe the detailed structure of atoms and molecules but also test the invariance of the velocity of light as postulated by the theory of special relativity, which has allowed us to redefine the SI unit of length and realize it in terms of experimental observables of quantized systems rather than physical artifacts.

The SI unit of length was originally intended to be one ten millionth part of the quadrant of the Earth, and the original 1799 metre was based on measurements made along a meridian from Dunkerque to Barcelona represented an attempt to realize this length. Such a physical artifact remained in the definition of the metre until 1960 when the definition was replaced by one based on a measurement of the wavelength of orange light emitted by excited atoms of an isotope of krypton. This definition was eventually superseded in 1983 by the present one, which is derived by assigning a defined value to the speed of light in free space. Today, the SI unit of the metre is ‘the length of the path traveled by light in *vacuum* during a time interval of $1/299\,792\,458$ of a second’, thus fixing the velocity of light at $299\,792\,458\text{ m s}^{-1}$.

With a fixed velocity of light relating distance and time, and hence frequency and wavelength, the ability to measure time more accurately than other physical quantities provides a much improved realization of the metre. In principle, one limited only by the accuracy of the time reference.

Research in the late 1990s demonstrated that the spectrum of light emitted by a mode-locked femtosecond laser could be used as a precise frequency “ruler” as they give rise to a series of regularly spaced frequency spikes called a “frequency comb”. It was demonstrated that such a frequency comb, within an appropriately broadened frequency output generated by using non-linear optical effects (such as the optical Kerr Effect), and referenced to a stable radiofrequency source could be used to measure an optical frequency. In addition, it was seen that because of the high quality of the femtosecond laser spectrum, the measurement of optical frequencies could be made with an accuracy essentially limited by the radiofrequency standard used as reference.

The developments in optical comb technology represented by the measurements of Long-Sheng Ma *et al.* (a collaboration involving the Bureau International des Poids et Mesures, Sèvres, France; Physics Department, East China Normal University, Shanghai, China; National Institute of Standards and Technology, Boulder, CO, USA; and OFS Laboratories, Murray Hill, New Jersey, USA), recently reported in *Science* (19th March, 2004), demonstrate the potential to connect the frequency of radiation in the optical range of the electromagnetic spectrum to the frequency of radiation in the radiofrequency domain with an accuracy approaching one part in 10^{19} . This remarkable result (one would be hard pressed to imagine any other field of science where such a degree of accuracy is possible) not only opens up ways to further improve our understanding of many problems in physics, but also allows for

significant technological advances and novel practical applications. The development of optical clocks with extreme accuracy will lead to advances and refinement of existing and even create new areas of physics and technology. For example, at present the best microwave time standard based on transitions within caesium atoms has an accuracy of about one part in 10^{15} , whereas the best optical frequency standards (spectroscopy of laser cooled single atoms and ions) are expected to approach a level of one part in 10^{18} . However, such an accurate and stable system is of little use if its frequency cannot be readily distributed to users and compared to other standards operating at very different frequencies without adding to the measurement uncertainty. The ability to make such connections between sources of different frequency leads naturally to questions such as, whether clocks realized in very different frequency regions (from the radiofrequency to the optical) will keep time at the same rate, and will this allow us to gain a better insight into general relativity whose union with quantum mechanics still remains elusive.

With the development of optical frequency standards and femtosecond frequency synthesizers or frequency combs, it will be possible to construct a functional optical atomic clock at these levels of precision. Such a development will undoubtedly lead to new discoveries and new insights. For example, with the levels of precision that are now becoming attainable it will be possible to determine fundamental constants with increased precision. These measurements may lead to the observation that these 'constants' vary spatially or change with time, a phenomenon which has been suggested by theoreticians and which would have profound consequences for our view of the universe and its evolution. On a more applied level, this new technology of optical frequency metrology will have applications in satellite navigation, communications and the synchronization of computer networks, and lead to technology which will out perform today's caesium clocks.

For editors

The *Bureau International des Poids et Mesures* (BIPM) was established by the authority of the *Metre Convention* in 1875, and is charged with providing the basis for a single, coherent system of physical measurements throughout the world. In 1875 the chosen system of units was the metric system. Over time this decision evolved and in 1960 it was decided that the chosen system of units was to be the International System of Units (SI). This system is not static but evolves to match the world's increasingly demanding requirements for measurements at all levels of precision and in all areas of science and technology.

For questions relating to the BIPM please contact Professor Andrew Wallard, Director, at awallard@bipm.org or Dr Jeffrey Williams, Head of Publications, at jwilliams@bipm.org.

For questions about the technical details of this new research, please contact Dr Lennart Robertsson at lroberts@bipm.org.