The absolute measurement of optical frequencies

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In 1999 the principle of self-phase modulation of an ultra short optical pulse in a non-linear fibre led to the establishment of a new type of frequency chain.

This frequency chain enabled the measurement of optical frequencies using radio frequency (RF) techniques, a feat previously only possible with rooms full of equipment. This wonderful development has enabled relatively simple measurement of Terahertz (THz) frequencies with unprecedented accuracy.

The CSIR – National Metrology Laboratory (CSIR-NML) plans to establish a frequency comb facility for the measurement of these frequencies. The facility will house two femtosecond frequency combs, one for the wavelength range from 400 nanometer (nm) to 1 100 nm utilising a mode-locked Ti:Sapphire laser, and the other from 400 nanometer (nm) to 1 100 nm utilising a novel femtosecond (fs) fibre laser based comb for the wavelength region from 1 micrometer (µm) to 2 µm. This will enable the measurement of optical frequencies in the range from 400 nm to 2 µm, with direct traceability to the national standard for time in South Africa.

The stability of a frequency standard is dependent on a number of factors, one of these being the frequency of the transition that is used as the oscillator for the standard. Another important factor is the observation time for the transition being used. RF frequency standards, such as rubidium vapour clocks, caesium clocks and hydrogen masers typically operate at several Gigahertz (GHz).

The caesium beam atomic clock operates at a frequency of around 9 GHz, with a relatively short observation time for the energy level transition. These standards recently received a performance boost by the development of atomic fountain technology. This increased the observation times to about a second. The best accuracy caesium fountain clocks in existence have accuracies and stabilities in the order of 10^{-15}. The theoretical limit for these clocks is a few parts in 10^{15}.

Clock accuracy has shown a remarkably stable increase in accuracy over the last fifty years. The accuracy of clocks has improved by about 1 order of magnitude every seven years. Due to the accuracy limits mentioned above, it is clear that some other technology will be required for clocks of the future. Several technologies have been proposed for these clocks, including putting RF clocks in space to reduce uncertainties due to magnetic and gravitational field fluctuations. Nonetheless, RF techniques are fundamentally limited in accuracy.

Optical transitions occur at much higher frequencies, being in the THz region. The biggest problem with optical transitions is that until recently it has been impossible to measure the frequency of these transitions accurately. No counter that directly counts THz frequencies exists.

Traditional frequency chains

The measurement of optical frequencies has been a research direction for a number of national metrology institutes (NMIs) over the past few decades. These traditional frequency chains, literally “chained” together a number of lasers to reach the RF region from the optical region. These chains usually occupied many laboratories, and consisted of numerous lasers.

At every frequency junction the frequency of one laser is compared to another and with each comparison, additional uncertainties are introduced. With many steps in the conversion from the optical domain, where the transition of interest is, to the RF domain, where frequency can be measured accurately, the uncertainty accumulates rapidly. This leads to relatively large uncertainties for the measurement of the frequencies of optical transitions.

An example of the measurement of an optical transition utilising a traditional frequency chain is the measurement of the frequency of the 5s 2S1/2 – 4d 2D5/2 transition in a single trapped 88Sr+ ion at 445 THz [1].

This measurement required the use of six lasers; numerous phase locked loops, a microwave klystron, X-band oscillator, H-Maser and several counters and ancillary equipment.

As an example, four CO2 lasers and two microwave oscillators are required to bridge the gap between the RF (5 MHz) and the infrared (32 THz, about 10 µm wavelength) region.

The value for the transition was obtained with measurements stretched over 15 months, with improvements coming from optimisations in each phase locked loop and stability improvements in each of the lasers systems over that period.

The measurement of the frequency had a standard uncertainty of 4.5×10^{-13}. Although this work represented a 100-fold improvement over previous measurements, it is still very far away from the theoretical limits achievable with these frequency standards.

Modern frequency chains

Modern frequency chains had to wait for a number of key discoveries. One of these was the availability of very high repetition rate fs lasers, and when it was discovered that self-phase modulation of ultra-short optical pulses takes place in non-linear optical fibre, the complexity...
and effort of optical frequency measurement reduced dramatically. This made possible a new type of frequency chain, based on optical frequency comb generators [2].

These new frequency chains allowed huge frequency differences to be bridged in a single step. The stability and accuracy of these combs were proven to be at least as good as the experimental boundaries, those being a few parts in $10^{15}$. In addition, this technique allows for relatively rapid measurements to take place. Typical optical frequency measurement within the range of such a device can be made within a single day. These optical frequency combs produce more accurate results than traditional frequency chains, and can produce these results in a very short space of time.

**The fs laser frequency comb**

The operational principle of a fs frequency comb is based on spreading a single frequency across a wide range of frequencies. Several techniques exist that allow this spreading to occur. The most commonly used technique is spectral broadening in a non-linear fibre. The first fs combs covered a wavelength range of several tens of nanometers. Today commercial devices are available that span more than an octave. Compact optical frequency combs operating in the visible range are relatively inexpensive, and this is a step. These devices produce a comb of frequencies spanning more than an octave [3].

The ultra-short pulses (in the time domain) produced by the fs laser produces a frequency spectrum that is spread out, with distinct fingers (or comb elements) in the frequency domain. Since the pulse repetition rate is fixed, these elements are equally spaced in the frequency domain. The repetition frequency is easy to measure and control. (Ti:Sapphire lasers normally operate at repetition frequencies between 80 MHz and 1 GHz.)

Due to a phase shift between the carrier frequency and the envelope function of the electromagnetic wave produced by the fs laser, the comb is offset from zero. This offset frequency is measurable, and can be fixed with a feedback control loop. Since the frequency comb spans more than an octave it is possible to self reference [4] the comb, using a comb element at a frequency that is twice the frequency of another comb element (see figures 1 and 2).

The 400 nm to 1100 nm compact optical frequency comb consists of a pumping laser, a high repetition rate fs Ti:Sapphire laser, a short piece (typically about 20 cm) of nonlinear fibre, optics and electronics for determining and phase locking the repetition rate and the offset frequency of the comb.

In Fig. 3 a fs frequency comb is shown.

As can be seen, both the repetition frequency and the offset frequency can be measured and controlled. The oscillator that is used to control the frequency loops provides the traceability to the comb. This can be either an optical transition, or a radio frequency source. In this way a frequency standard can be made that bridges the gap from the optical to the radio frequency domain in a single step.

**CSIR-NML projects**

**Acetylene stabilised laser**

In 2002 the CSIR-NML started a project on the stabilisation of a diode laser to the absorption in acetylene gas at low pressure. Acetylene has absorption lines in the 1550 nm wavelength range. This range is utilised for communications, and the demand for higher accuracy calibrations in this wavelength range has increased. The project produced a functioning device used in the calibration of optical spectrum analysers (OSAs) and wavemeters, with an uncertainty about two orders of magnitude smaller than the previously available calibration source.

Further development of this laser is currently underway to produce narrower absorption lines by utilising a technique called sub-Doppler spectroscopy. This development will further reduce the uncertainty of the laser frequency.

**Rubidium stabilised laser**

More than one wavelength is required for the calibration of OSAs. At present these devices are calibrated using the acetylene stabilised laser in the region of 1550 nm only. Most of these devices have a working range that extends down to 700 nm, and some have a working range extending down to 600 nm. For the devices with working ranges extending down to 600 nm, a He-Ne stabilised laser at 633 nm can be used as a second calibration point. For the other devices, no suitable reference is currently available at the CSIR-NML.

Due to this requirement, it was decided to build a second system stabilised on a suitable transition in the lower wavelength ranges. Rubidium has an absorption line in the region of 780 nm. The diode lasers in this wavelength range are relatively insensitive, and this is a very common experiment [5], making it an ideal wavelength to use as a second reference point for the calibration of OSAs.

The aim of the project is to deliver a laser with a stable and known output wavelength for the calibration of OSAs. The laser is an extended cavity device built using the Littman [6] configuration. The CSIR-NML design is based on a recent design by the Academy of Sciences of the Czech Republic [7].

An 80 mW laser diode will be used in the project. The laser will be housed on a breadboarding
approximately 600 mm x 600 mm, and will be transportable to enable the easy transportation of the system between laboratories.

**Frequency comb facility**

A frequency comb facility will be established at the CSIR-NML within the next year. The facility will enable the measurement of optical frequencies in the range 400 nm to 2 µm. It will consist of two frequency combs, one covering the wavelength range from approximately 400 nm to 1 100 nm, and the other covering the range from 1 µm to 2 µm.

The facility will include a high stability local oscillator, such as a passive hydrogen maser (microwave amplification by stimulated emission of radiation), to provide the short-term stability required by the frequency combs. It will also include high quality optical tables and the components required for the measurement of optical frequencies.

The comb covering the wavelength range from 400 nm to 1 100 nm consists of a mode-locked Ti:Sapphire laser with a repetition rate of about 1 GHz, and a pulse width of less than 100 fs. These pulses are then launched into a piece of non-linear fibre. In the fibre, self-phase modulation of the pulses takes place, which broadens the frequency spectrum of the output signal to cover the wavelength range of interest. A more detailed discussion of this device is given earlier in the paper.

The comb covering the wavelength range from 1 µm to 2 µm works on the same principle. In this case the fs pulses are generated in an erbium doped fs fibre laser, and the spectrum is broadened in a piece of non-linear fibre.

The combination of these two combs will provide access to accurate optical frequency measurements throughout the range from 400 nm to 2 µm.

The lasers currently used for realisation of the meter at the CSIR-NML will be measured against the frequency comb, and it is envisaged that the frequency comb will be designated as the national standard for length sometime in the future. The facility will also enable the CSIR-NML to measure the frequency of its other lasers in absolute terms, including the acetylene stabilised laser system, and the rubidium stabilised laser.

The development of an optical clock is planned as a platform project for the CSIR-NML. This project will produce a high accuracy frequency standard for South Africa, and provide exciting research opportunities to scientists. Several enabling technologies will have to be put in place before this research can be undertaken, and the frequency comb facility is the first of these. The frequency comb facility will be made available to other researchers in South Africa interested in optical frequency measurement research.

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**References**


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