The Era of Coherent Optical Frequency References

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In the past four years have shown a dramatic improvement in the performance of optical frequency references and in the methods by which they are calibrated and utilized. These revolutionary changes result from better stabilized lasers that probe narrow-linewidth transitions in laser-cooled atoms and ions, and from the development of a convenient method for synthesizing, measuring and distributing optical frequencies based on mode-locked lasers.

Physical Wavelength References

Frequency stabilized lasers are usually controlled by some type of physical artifact that has good mechanical stability and that uses optical interference to provide wavelength discrimination and selectivity. High spectral resolution is made possible with high quality optics and optical interference. An optical interferometer might consist of optical gratings, solid etalons, Fizeau or Michelson interferometers, or Fabry-Perot cavities. The very best of these instruments can provide outstanding stability on short time scales and reasonable accuracy (10^{-4} to 10^{-9} fractionally). For short time intervals and in highly controlled environments Fabry Perot cavities provide very high spectral resolution ($\frac{\Delta\lambda}{\lambda} \approx 10^{-12}$) and the very best short-term stability (eg. $\frac{\Delta\lambda}{\lambda} = 10^{-15}$ for times $\tau <$ 20s).[i] The geometrical stability of even the best physical artifacts is limited by material properties, environmental effects and history. If the interferometer path-length is not entirely evacuated the temperature dependence of the refractive index combined with temperature fluctuations can dominate the wavelength instability (e.g. 10^{-5}/K for quartz). In addition, even the best physical artifacts show dimensional changes with time due to material aging and creep. This might be on the order of 10^{-7}/yr for good materials, and depends strongly dependant on environmental history. For transportable instruments it seems quite challenging to achieve better than ~100 MHz frequency uncertainty in the visible (~500 THz) even using high quality vacuum-spaced temperature controlled Fabry-Perot cavities. When higher accuracy and better long-term stability are required, atomic and molecular transitions provide a good solution.

Quantum Frequency References

Atomic and molecular energy levels provide discrete frequency references determined by quantum mechanical interactions ($E_i - E_j = h\nu_{ij}$). These can serve as high accuracy frequency markers to control laser frequencies. A fundamental difference between physical artifacts and quantum systems for frequency control is that physical references act as wavelength references while atomic transitions are frequency references. Interferometers depend directly on geometrical factors (optical path lengths, angles, index of refraction, etc.) and discriminate wavelengths by multi-path interference, whereas atomic/molecular transitions depend on quantum mechanical energy differences and hence optical frequency. The physical parameters of artifacts are difficult to control with high accuracy and for long periods of time. Quantum references provide much better long-term stability and accuracy, but have some disadvantages that include: signals that are generally weaker than those achieved with physical references, quantum transitions are usually not conveniently distributed in wavelength, and the detection of atomic states is generally more complex and less robust than physical references. They can however provide an absolute frequency reference which is known (with varying degrees of accuracy) in terms of the fundamental constants and SI units, in particular the Cs atomic frequency (9 192 631 770 Hz) that defines the SI "second". Rough estimates of the performance achieved with common types of optical wavelength/frequency references are provided in the figure 1.

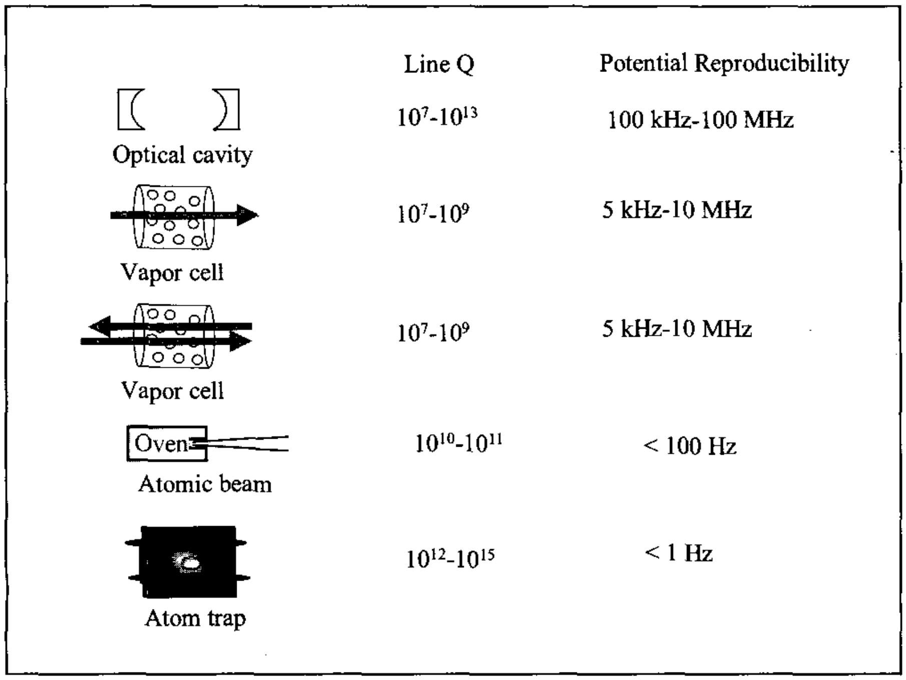

Figure 1. Approximate frequency reproducibility attained with different types of optical frequency references. The second column gives the range of spectral line Q's that is achieved, where Q = (center frequency)/(linewidth). The third column gives approximate frequency reproducibility assuming a center frequency near 500 THz. The wide range of values shown here results from the fact that the performance depends strongly on the actual system and environmental conditions. Two different types of vapor cell systems are illustrated. The single laser beam system represents Doppler broadened transitions, while the two-beam system corresponds to Doppler-free methods, such as saturated absorption or two-photon transitions. The atom/ion trap example is for laser-cooled atoms/ions with near zero thermal velocity.

Most of the atomic/molecular transitions that are commonly used as optical frequency references have been reviewed elsewhere, so Table 1 lists only a few representative examples that illustrate the distribution in wavelength and the performance that has been demonstrated. Some research groups are studying optical atomic frequency standards for their potential in providing the highest possible frequency stability and accuracy for the next generation of atomic clocks, while other groups are developing simpler compact optical frequency references with more modest performance that can be used as calibration references for field applications such as WDM systems.[ii,iii,iv,v,vi,vii,viii ix,x] Some representative examples of quantum transitions currently being used for optical frequency references are provided in Table 1.

Atom	λ (nm)	Linewidth (kHz)
Ca	657	0.4
Sr	689	7
Mg	457	0.4
Cs	852 & 891	5000
Rb	780 & 795	5000
Rb	778	300
I_2	500-700	50-5000
H	243	0.5
C_2H_2	1530-1560	<1000
CH_4	3392	3
Hg^+	281	0.006
Yb^+	435	0.010
Sr^+	674	0.050

Table 1. Some representative optical frequency references. The first column lists the atom/ion/molecule, the second column gives the wavelength of the reference transition(s), and the third column provides an approximate spectral linewidth observed experimentally on that transition. More details can be found in the references.

Optical Frequency Combs

Modern mode-locked lasers can now be actively stabilized to produce a fixed comb of optical frequencies which can be used to translate optical frequencies coherently from one spectral region to another, ranging from the ultraviolet to the microwave region. The basic concept of performing optical frequency synthesis using mode-locked lasers is based on ideas from T. Hänsch and others.[xi,xii] Today, ultra-fast mode-locked lasers have repetition rates of 50-1000 MHz and produce optical pulses with pulse widths in the 5 to 100 fs range. This repetitive train of optical pulses, with pulse-width Δt_p and repetition rate f_{rep}, has a Fourier domain spectrum that consists of a comb of optical frequencies separated by f_{rep} and covering a spectral-width of Δf_{opt} as illustrated in figure 2. When appropriately stabilized and viewed in the Fourier domain, the pulse train corresponds to an evenly spaced array of modes (e.g. an "optical frequency comb") that covers a significant portion of the optical spectrum (~100 THz). The frequency of all the modes can even be determined with accuracy equal to that of the best atomic clocks.

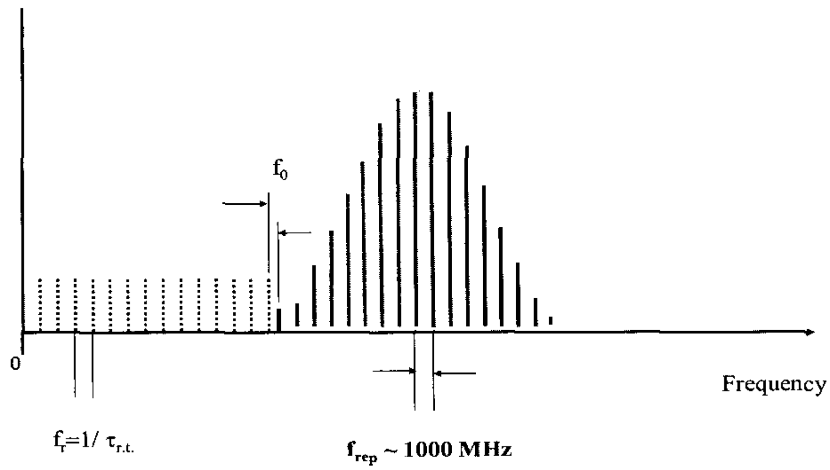

Fig. 2. Schematic representation of an optical frequency comb showing the mode spacing set by the pulse repetition frequency f_{rep} and offset from zero by f_0 when extrapolated to zero frequency. The series of dotted lines represents an imaginary comb of modes that starts at zero frequency and progresses toward higher frequencies with a mode spacing equal to f_{rep}.

The frequency of any arbitrary mode N (an integer) of the optical comb can be written simply as $f_N=Nf_{rep}+f_0$ where f_0 is an offset frequency of the comb from zero (if it was hypothetically extended all the way back from optical to zero frequency). The repetitive optical pulses, or equivalently their frequency domain comb of modes serve as the key component of the new optical frequency synthesizers. As can be seen in the equation above, there are two free parameters to the comb: the spacing of the comb modes determined by f_{rep} and the offset of the entire comb f_0. To know the exact optical frequency of all the modes of the comb requires that we determine and control two free parameters. These could be f_{rep} and f_o (two frequencies in the radio frequency domain), or the frequency of two specific optical modes f_i and f_j (in the optical domain), or f_o and a specific optical mode f_i. The most powerful approach is the "self reference" method demonstrated in 2000.[xiii] In that method some low frequency comb modes are frequency doubled and then compared with a some high frequency modes, generating a beatnote that provides a radio frequency output equal to the offset frequency f_0, thus $2(kf_{rep}+f_0) - [2kf_{rep}+f_0]=f_0$, where i is an integer. Table 2 lists some examples of mode-locked laser based optical frequency combs that are being used for optical frequency measurements.

Type of mode-locked laser	f_{rep} (MHz)	Pulse-width (fs)	External broadening	Wavelength range (nm) approx. w/ broadening	Freq. Meas.	Self-Referencing method
Ti:sapphire	80 to 1000	<50	Microstructure fiber	500-1200	Yes	f-2f
Ti:sapphire	1000 and 100	<10	None required	550-1100	Yes	2f-3f and f-2f
Fiber laser	50	50-100	Highly nonlinear fiber and microstructure fiber	800-2200	Yes	f-2f
Cr:Forsterite	430	40	Highly nonlinear fiber	1000-2200	Yes	f-2f
Cr:LiSAF	90	40	Microstructure fiber	550-1100 nm	No	f-2f

Table 2. Some optical frequency combs based on mode-locked lasers that are being used for optical frequency measurement, distribution and control.

Summary

The new tools and methods outlined very briefly enable precise control of the phase and frequency of laser fields. The key ingredients making the advances possible are: stabilized optical frequency combs, highly stabilized continuous-wave lasers, and precision spectroscopy of laser-cooled atoms and ions. Combining these technologies in just four years has led to ~1000 times improvement in the performance of optical frequency references. These capabilities represent a new era in optical frequency synthesis, metrology, and coherent optical control. Obviously, there is a direct analogy and correspondence with the well-known coherent techniques now widely used in RF and microwave electronics, and perhaps there will be similar widespread applications in optics in the future. Phase and frequency control methods are improving spectral resolution by many orders of magnitude. For example, it is challenging to get 7 digits of wavelength accuracy by interferometric methods, whereas 15 digits of frequency accuracy has been demonstrated at optical frequencies. In spite of this, we must still recognize that the five most significant digits are still most easily determined interferometrically rather than by the methods of optical frequency metrology. Some combination of the two approaches, interferometry and frequency metrology, seems most widely useful and applicable. Coherent optical methods are not a new idea; they were suggested long ago for numerous applications including optical communication systems, sensing, lidar etc. However, <u>now</u> is the time that these ideas are coming to fruition and becoming an experimental reality. This enables many older ideas and applications, and opens new frontiers such as optical atomic clocks, timing and synchronization with femtosecond precision, ultra-low phase-noise microwave sources, and, no doubt other applications to come.

References

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