LOCKING A LASER FREQUENCY TO THE TIME STANDARD

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On the basis of high-frequency modulation experiments and well-known locking techniques, a scheme is described for stabilizing a visible laser frequency and simultaneously determining that frequency in terms of the time standard. The importance of this method for a refined determination of the velocity of light and the possibility of establishment of reference lines for spectroscopy and for length measurements, throughout the spectrum wherever laser lines are available, is discussed.

We have demonstrated in our recent experiments[1] that an electrooptic intracavity amplitude modulation of a 6328-Å He–Ne laser is practicable at frequencies, ω, up to 25 GHz. The yield in the side bands, $\nu \pm \omega$ (where ν is the laser frequency), exceeded 10^{11} photons per second. There were no indications in the experiments that these numbers should be considered as upper limits. These results, along with the ability demonstrated by many experimenters[2-5] to lock a laser to a passive reference cavity assures one of the feasibility of locking the frequency of a visible laser line to a microwave frequency, and of relating thereby that optical frequency to the time standard. The method for accomplishing this as being pursued in this laboratory is as follows.

The difference frequency between the sidebands is known (2ω), and the ratio $(\nu + \omega)/(\nu - \omega)$ can be established as corresponding to the ratio N_+/N_- of the two order numbers N_+ and N_- of a passive cavity, when that cavity is tuned simultaneously to both frequencies.[6] Then, using the first approximation theory of Fabry–Perot cavities,

$$\begin{aligned} \nu + \omega &= N_+(c/2L) \\ \nu - \omega &= N_-(c/2L) \ , \end{aligned} \quad (1)$$

where c is the velocity of light and L is the length of the interferometer cavity. Thus,

$$\nu = 2\omega(N_+/n) - \omega = 2\omega(N_-/n) + \omega \ , \quad (2)$$

where $n = N_+ - N_-$.

Hence, ν is established relative to ω and is known if the integer order numbers N_+ and N_- are known. It is seen from Eq. (2) that neither the knowledge of the velocity of light nor that of the length of the cavity is required in the measurement of ν, even though both are important parameters in the operation of the cavity.

In order to realize by servo mechanisms the two conditions as expressed by Eqs. (1), two error signals are needed. At a preset value of ω, L and ν must be driven to the appropriate values. The two error signals can be derived by sweeping ω through $\beta \cos 2\pi\gamma_\omega t$ and simultaneously sweeping L through $b \cos 2\pi\gamma_L t$. Both γ_ω and γ_L are low frequencies with respect to the bandwidth of the interferometer (in our apparatus $\gamma_\omega = 2$kHz and $\gamma_L \simeq 50$ kHz). The amplitudes β and b are chosen to be about the half width of the Fabry–Perot transparency function.

The ω sweep moves the side-band frequencies in opposite directions. Thus the contributions to the error signal (the transmitted light intensity, phase detected at γ_ω) will be of opposite sign for the two side bands. When the length L is appropriate to ω these contributions cancel and the error signal is zero. This error signal is used to servo L to ω.

The error signal phase detected at γ_L is used to servo the length of the laser cavity, and consequently ν, to L. It should be emphasized that the error signals detected at the frequencies γ_L and γ_ω, though coming from the same photodetector, are independent if these two frequencies are unrelated. Thus the two servo systems work simultaneously (Fig. 1).

The error signal detected at γ_ω is highly insensitive to fluctuations in ν, because this signal is the sum of the contributions of opposite sign from the two side bands. Each of those components may undergo significant fluctuations (due to fluctuations in ν) but those fluctuations are strictly correlated and cancel in the algebraic sum. The only uncorrelated part is that due to shot noise. Therefore a long integration time can be used to overcome shot noise limitations. With photoelectron currents of 10^{10} electrons per second in each side band and a one second integration time(relative shot noise fluctuation $\sim 10^{-5}$) the setting of the interferometer length to $\delta L/L \sim 10^{-5}\Delta\nu/2\omega \sim 10^{-9}$ is expected if the finesse $F \sim 100$, L is of the order of one meter ($\Delta\nu = c/2LF \sim$ 1.5 MHz), and $\omega \sim 10$ GHz. This corresponds to setting L to 1/3 of the fringe-width (~ 10 Å).

Thus, the simultaneous operation of the two servo systems readily assures setting of the optical frequency, ν, to 1 part in 10^9 (~ 500 kHz).

A more exact statement of Eq. (2) which does not neglect diffraction and reflection phase shifts is

$$\nu = 2\omega[N_+/(n + \mu)] - \omega \ . \quad (2a)$$

The μ which incorporates the effect of phase shifts can be determined to the necessary accuracy (sufficient to utilize the achieved accuracy of L) by well-known techniques of interferometry, that is, by using a fictitious cavity length which is the difference in length between two successive settings of the interferometer.

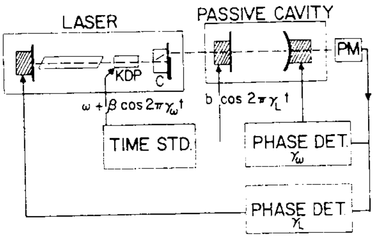

Fig. 1. Locking a laser frequency to a frequency standard. The 6382-Å He–Ne laser is modulated electrooptically by an intracavity KDP crystal driven at the microwave frequency ω; the side bands $\nu \pm \omega$ are coupled out by a calcite plate C, their polarization being opposite to that of the main laser beam; ω is locked to a frequency standard and is also swept at a low frequency γ_ω. The side bands pass through the passive cavity and are detected in the photomultiplier, PM. The length of the passive cavity L is modulated at the frequency γ_L. The output of the PM, as phase-detected at γ_ω servoes L, and as phase-detected at γ_L, simultaneously servoes the laser. The result is that the passive cavity is tuned to both side bands and ν is stabilized to ω.

The precision of the above method may be increased by increasing (1) the length and/or the finesse of the interferometer; (2) the modulation frequency; (3) the intensity of the side bands; (4) the integration time of the length servo. The ultimate long term stability is limited only by that of the time standard.

It should be emphasized that, while consisting of components performing similar operations, the above scheme differs from those of Refs. 2–5 in the sense that in those experiments the passive cavity is locked to atomic or molecular resonances, individually chosen for each laser line. In the present scheme one single resonance transition is used for any ν, namely, that of the frequency standard. This automatically relates every ν to the internationally accepted frequency scale. Thus direct frequency measurements which have already been achieved in the far infrared[7,8] may be compared with future measurements made in the visible without the difficulties inherent in the intercomparison of wavelengths in distant parts of the spectrum.

The above method of stabilization and frequency measurement is applicable to any laser line. Also, the frequency of laser lines, stabilized by other means, can be measured by these techniques. Thus, as one important application of these ideas, reference lines for spectroscopy can be established throughout the spectrum wherever laser lines are available.

Another application is the evaluation of the velocity of light. It is obvious that the knowledge of the frequency in terms of the standard second and a simultaneous measurement of the corresponding wavelength in terms of the length standard results in refining the value of the velocity of light, c, in meters/second. Since it is expected that the accuracy of the ν measurement will surpass that of the definition of the present length standard, the accuracy of c will be limited to that of the present meter, about 1 part in 10^8. A definition of c (compatible with the present meter, but otherwise arbitrary) would result in a new definition of the meter. As the above method is applicable to any laser line, reference wavelengths for precise length measurements would be available in any part of the optical spectrum without the need to define one particular wavelength as a new length standard. Also, time of flight measurements (in terrestrial and space radar) could be translated directly into distances via the definition of c.

[1] Details to be published later. Our experiments extend the work of R. Targ, G. A. Massey, and S. E. Harris, Proc. IEEE, 52, 1247 (1964), to higher modulation frequencies.
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