Calibration of laser frequency scan with an electro-optic modulator

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An electro-optically modulated laser beam was used to excite the Yb $^1S_0(6s)^2 \rightarrow {}^3P_1(6s6p)$ transition. Fluorescence was recorded as the laser frequency was scanned across the transition. Each isotope generated multiple peaks in the spectrum separated by the modulation frequency that permitted the frequency scan to be calibrated. The resulting isotope shifts agree well with existing data obtained with an interferometer to monitor the change in laser frequency. Electro-optic modulators have the advantages of being relatively inexpensive and simpler to operate than interferometers whose length must typically be stabilized with a laser whose wavelength is locked to an atomic transition. © 1997 Optical Society of America

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The spectroscopic technique of scanning a laser frequency across a resonance while detecting fluorescence is invaluable for the measurement of frequency intervals such as Doppler shifts, Stark and Zeeman shifts, fine and hyperfine splittings, linewidths, etc.[1] An essential step in these measurements is the accurate calibration of the frequency scan that is usually done when part of the laser beam is passed through an interferometer.[2] A maximum in laser transmission through the cavity occurs whenever the laser frequency changes by an amount equal to the cavity's free spectral range ν_{FSR}. For a confocal Fabry–Perot étalon, $\nu_{\mathrm{FSR}} = c/4nL$, where c is the speed of light, L is the cavity's length, and n is the index of refraction of the material (usually air) inside the interferometer. The accuracy of this method is limited by vibrations, temperature, and pressure fluctuations that change the optical length of the cavity. Hence the cavity length must be stabilized with a reference laser that must itself be locked to an atomic transition for an accurate calibration.[3] Unfortunately, this apparatus is relatively complex and expensive and not available to many scientists.

In this paper we show how the frequency scan can be calibrated with an electro-optically modulated laser beam. Optical modulators have been used recently to precisely determine frequency intervals.[4–7] Modulation frequencies to several gigahertz are generated readily by frequency synthesizers with an accuracy of one part per million, which far exceeds the determination of a cavity's free spectral range. In this experiment, the laser frequency was scanned across a resonance and fluorescence was detected. Each transition was excited by the various frequency components of the laser beam generating multiple peaks in the fluorescence spectrum. These peaks are separated by the modulation frequency, permitting the frequency to be calibrated. In this paper we determine the isotope shifts of the ytterbium $^1S_0(6s)^2 \rightarrow {}^3P_1(6s6p)$ transition and compare the results to those obtained with a Fabry–Perot étalon. Yb has naturally occurring isotopes with atomic mass units 168 (0.13%), 170 (3.05%), 171 (14.3%), 172 (21.9%), 173 (16.12%), 174 (31.8%), and 176 (12.7%). The nuclear spin for the even isotopes is zero, whereas isotopes 171 and 173 have spins of 1/2 and 5/2, respectively.

The apparatus is similar to that described elsewhere and is therefore only briefly discussed here.[4] An atomic beam was generated in a vacuum with an oven and a series of collimating slits. The laser light at a wavelength of 555.6 nm was supplied by a ring dye laser (Coherent 699). The laser beam passed through an electro-optic modulator (ν-Focus 4421) that could frequency shift over 50% of the incoming light for modulation frequencies in the range of 995 to 1005 MHz. The modulation signal was supplied by a Hewlett-Packard 8647A signal synthesizer with an

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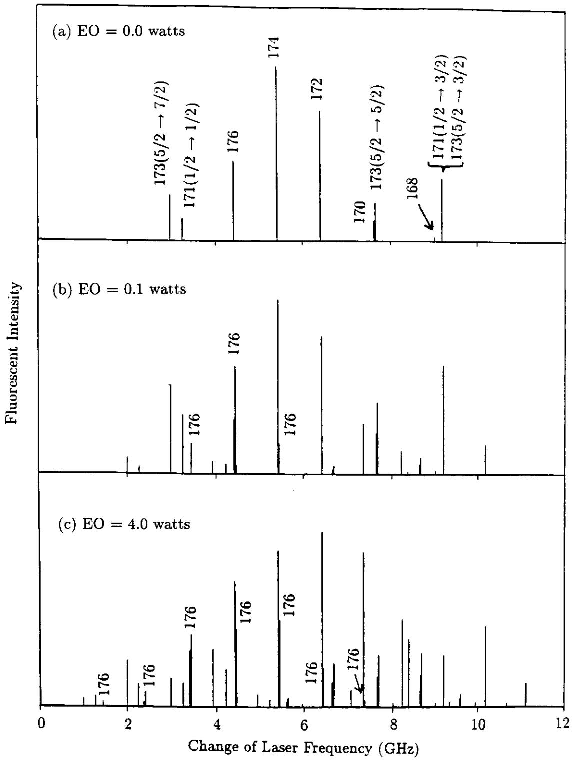

Fig. 1. Frequency scan of laser across Yb $^1S_0(6s^2) \rightarrow {}^3P_1(6s6p)$ transition. (a) 12-GHz scan obtained when the laser was not frequency modulated. (b) Data observed when a power of 0.1 W was supplied to the electro-optic modulator. The first-order frequency sidebands of the laser excited the transition. (c) This scan was taken with a power of 4 W supplied to the electro-optic modulator and shows the excitation of the transition by the second-order and third-order laser frequency sidebands. The modulation frequency was 1000.000 MHz.

Table 1. Isotope Shifts of the ytterbium $(6s)^2\,{}^1S_0 \rightarrow (6s6p)\,{}^3P_1$ Transition

	Position Relative to ^{176}Yb (MHz)		
Spectral Line	Ref. 3	Ref. 4	This Research
173(5/2 → 7/2)	−1431.7 ± 0.5	−1432.6 ± 1.2	−1430.5 ± 1.4
171(1/2 → 1/2)	−1177.2 ± 0.5	−1177.3 ± 1.1	−1175.8 ± 1.0
176	0	0	0
174	954.8 ± 0.5	954.2 ± 0.9	956.7 ± 0.8
172	1955.0 ± 0.5	1954.8 ± 1.6	1956.4 ± 1.1
170	3241.5 ± 0.5	3241.5 ± 2.8	3242.4 ± 1.5
173(5/2 → 5/2)	3266.5 ± 0.5	3267.1 ± 2.8	3265.5 ± 1.6
168	4610.1 ± 0.5	4611.9 ± 4.4	4611.0 ± 1.7
171(1/2 → 3/2)	4759.8 ± 0.5	4761.8 ± 3.7	4761.2 ± 1.7
173(5/2 → 3/2)	4760.4 ± 0.5	4761.8 ± 3.7	4761.2 ± 1.7

accuracy of one part in 10^6 and amplified to a power of 4 W (Amplifier Research 4W1000). The laser beam intersected the atomic beam orthogonally to eliminate the first-order Doppler shift. Fluorescence produced by the radiative decay of the excited state was detected by a photomultiplier. This signal was sent to a lock-in amplifier whose reference signal was provided by a chopper that modulated the laser beam. The lock-in digitized the demodulated signal while the laser frequency was scanned across the resonance. A 12-GHz laser scan took approximately 4 mins and consisted of approximately 64,000 points that were stored on a disk. Nearly 200 separate scans were taken.

Figure 1 shows typical data taken with a modulation frequency of 1000.000 MHz. Transitions in ^{171}Yb and ^{173}Yb are labeled by F, which is the sum of the nuclear spin and the electronic angular momentum. The signal shown in Fig. 1(a) was taken without any power supplied to the electro-optic modulator. Figure 1(b) shows the signal obtained when a power of approximately 0.1 W was supplied to the modulator. The presence of the first-order laser sidebands creates a spectrum in which each transition that appeared in Fig. 1(a) now occurs three times. Finally, Fig. 1(c) shows data obtained when a power of approximately 4 W was supplied to the modulator. This spectrum shows peaks generated by the second-order and third-order laser sidebands. We found the line center positions by fitting a Gaussian function to each peak.

We calibrated each laser scan by finding the average number of points corresponding to the frequency intervals representing the modulation frequency. Each point was found to correspond to a frequency interval of 0.1872 MHz. The frequency differences of the ^{173}Yb ($F = 5/2 \rightarrow F = 7/2$) and the ^{171}Yb ($F = 1/2 \rightarrow F = 1/2$) peaks relative to the nearest ^{176}Yb peak were then found. For example, the shift of the ^{173}Yb ($F = 5/2 \rightarrow F = 7/2$) peak relative to the peak excited by the first-order shifted laser sideband was measured to be −430.5 ± 1.4 MHz. This amount was then subtracted by 1 GHz to obtain −1430.5 ± 1.4 MHz given in Table 1. The isotope shifts of the ^{174}Yb and ^{172}Yb peaks were found with a modulation frequency of 985.000 MHz. A modulation frequency of 1 GHz was not used because the separation of the ^{172}Yb and ^{174}Yb peaks is nearly 1 GHz. The shifts of the remaining peaks were first measured relative to the ^{172}Yb peak. We found the shift relative to ^{176}Yb by adding the shift of 1956.4 ± 1.1 MHz, the amount separating the ^{172}Yb and ^{176}Yb peaks. The uncertainties given in Table 1 are the standard deviations of the data about their average value.

Several groups have examined this transition with Fabry–Perot interferometers whose length was not actively stabilized with a reference laser and obtained results having uncertainties as large as tens of megahertz.[8–10] Table 1 only lists the results of Clark *et al.* who used a confocal Fabry–Perot étalon with a free spectral range of nearly 300 MHz.[3] A He–Ne laser whose wavelength was locked to an iodine line was used to stabilize the cavity length. In addition, the étalon was housed in a vacuum chamber to eliminate pressure and temperature fluctuations. An earlier experiment by the same group did not enclose the Fabry–Perot cavity in a vacuum chamber and obtained isotope shifts that differed by as much as 4 MHz from their later results.[2,3] The ($F = 1/2 \rightarrow F = 3/2$) ^{171}Yb and ($F = 5/2 \rightarrow F = 3/2$) ^{173}Yb transitions were resolved with a magnetic field. The line centers were measured as a function of magnetic field, and the data were extrapolated to zero field to find the peak positions.

Table 1 also lists results found with an acousto-optic modulator to calibrate the frequency scan.[4] Acousto-optic modulators generate frequency sidebands that are spatially separated from the frequency-unshifted laser beam. Two of the laser frequency components differing by 300.000 MHz were superimposed with alignment slits. The exact overlap of the two frequency components of the laser is important since a differential alignment produces a different residual first-order Doppler shift. For example, an alignment difference of only 1 mrad between the two laser frequency components results in a 1-MHz uncertainty for a transition having a 1-GHz Doppler width. The two laser frequency components can be superimposed exactly if they are passed through a single-mode fiber.[11] The measurements made with the acousto-optic modulator are more sensitive to scanning nonlinearities than the present research since electro-optic modulators generate frequency sidebands having larger frequency shifts.

In conclusion, the isotope and hyperfine shifts of the $\mathrm{Yb}\,^1S_0(6s)^2 \rightarrow {}^3P_1(6s6p)$ transition found with electro-optic modulation agree well with the most accurate results determined with a Fabry–Perot étalon. The frequency calibration is simple and unaffected by vibrations, temperature, and pressure fluctuations that can strongly perturb interferometers. Frequency synthesizers also generate a much wider range of modulation frequencies than are available with the free spectral range of an interferometer. The modulation frequency can be changed quickly, whereas altering the length of an interferometer can be tedious. Alignment of the various frequency components of the electro-optically modulated laser beam relative to an atomic beam is also simpler than using an acousto-optic modulator because the latter generates frequency sidebands that are spatially shifted. Hence electro-optic modulators have a promising future for measuring frequency intervals such as isotope shifts and hyperfine splittings.

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