

Accurate wavelength calibration references for wavelength division multiplexing

Sarah L. Gilbert and William C. Swann
 National Institute of Standards and Technology
 M/S 815.03, 325 Broadway, Boulder, Colorado 80303
 ph. (303)497-3120, fax (303)497-7621
 sgilbert@boulder.nist.gov, swann@boulder.nist.gov

We describe two new wavelength standards that are very convenient to use and can provide a calibration uncertainty of 1 pm. Both are molecular gas absorption cells with rich absorption spectra in the spectral region where most wavelength division multiplexing (WDM) systems are being developed. We describe and quantify the effects that limit their accuracy, principally pressure shifts. We also describe a higher accuracy wavelength standard for National Institute of Standards and Technology (NIST) internal calibration.

Our moderate accuracy references are NIST Standard Reference Material (SRM) transfer standards based on rotational-vibrational transitions of acetylene, $^{12}\text{C}_2\text{H}_2$ (SRM 2517), and hydrogen cyanide, $\text{H}^{13}\text{C}^{14}\text{N}$ (SRM 2519). The $\nu_1 + \nu_3$ combination band of acetylene has more than 50 strong absorption lines in the 1510-1540 nm region. The absorption lines of the $2\nu_3$ overtone transition of hydrogen cyanide (Fig. 1) are more optimally placed for current WDM applications, with about 50 lines in the 1530-1565 nm region.

The SRMs were designed for calibrating wavelength measuring instruments such as optical spectrum analyzers and wavelength meters. The units are optical-fiber-coupled with single-mode fiber, and the spectrum can be observed using a broadband source (such as a light emitting diode or amplified spontaneous emission source) or a tunable laser. Single-wavelength calibrations using a single line, and scan linearity measurements using multiple lines can be made. NIST has evaluated the uncertainty of the line centers and provides certified wavelength values. Each SRM unit is measured at NIST to assure that it contains the correct gas pressure.

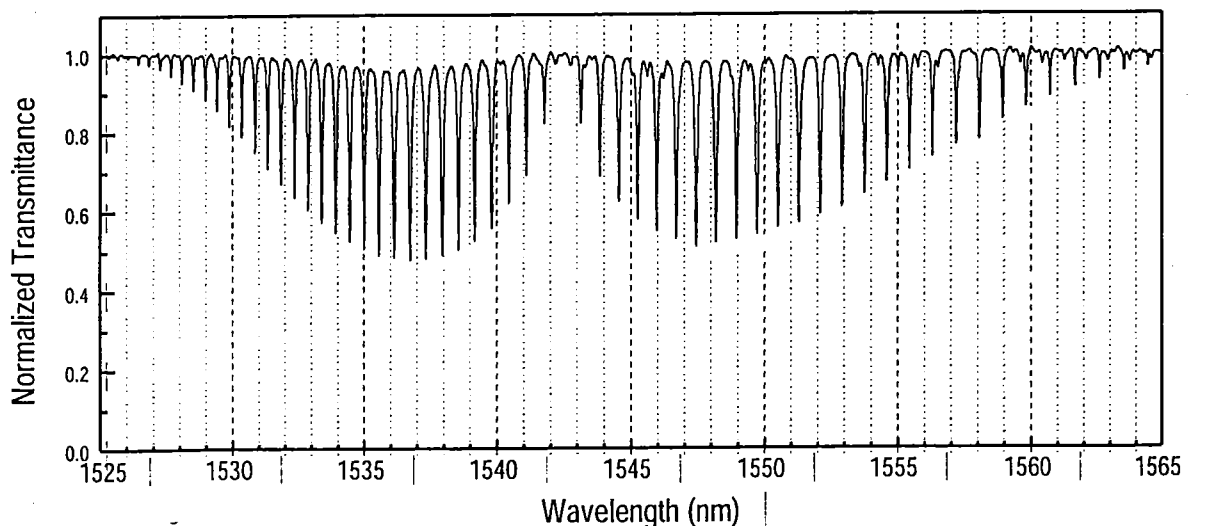


Figure 1 Hydrogen cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$) spectrum taken by passing LED light through a SRM unit and recording the spectrum of the transmitted light using an optical spectrum analyzer with 0.05 nm resolution. The figure shows the recorded spectrum divided by the LED spectrum. The HCN gas pressure is 13 kPa; light makes a triple pass through the cell for a total optical path length of 22.5 cm.

Fundamental molecular absorption lines are very stable, and their physical behavior is well understood. The vacuum wavelengths of the acetylene line centers have been measured with a quoted uncertainty of 1.2×10^{-6} nm,¹ and the vacuum wavelengths of the hydrogen cyanide line centers have been measured with a quoted uncertainty of 1.2×10^{-4} nm.² Although molecular and atomic structure is relatively insensitive to changes in environment conditions, it is not completely immune, and slight shifts of line centers can occur under certain conditions. The largest potential source of line shift is due to energy level shifts caused by the interaction of the molecules during collisions. This collision-induced line shift increases linearly with pressure and is often referred to as the "pressure shift." The line center values given in Refs. 1 and 2 are for very low pressure conditions and are applicable, at the quoted accuracy, only to that situation. To provide maximum signal when used with a 0.1 nm resolution instrument, such as an optical spectrum analyzer, the gases in the SRMs are at moderate pressures (27 kPa for acetylene and 13.3 kPa for hydrogen cyanide). Since our goal was to certify these SRM references with an uncertainty of 1 pm, we measured the pressure shift for both acetylene and hydrogen cyanide.

In the pressure shift measurement, light from a tunable diode laser was sent through two absorption cells simultaneously, one at low pressure and the other at higher pressure. The transmission through each cell was monitored by a detector. A wavelength meter with an uncertainty of 1 part in 10^7 (0.16 pm) was used to monitor the wavelength of the laser. Figure 2 shows the spectrum obtained for a hydrogen cyanide line. The pressure broadening in the high-pressure cell is obvious. We are interested in the relative shift between the line centers of the low-pressure and high-pressure cells. For the hydrogen cyanide measurement, we recorded 21 lines using this technique. The low-pressure cell contained gas at a pressure of 1.3 kPa (about 10 Torr) and the other cell contained a pressure of 12.6 kPa (about 95 Torr). A computer was used to scan the wavelength of the laser and record the readings of the two detectors and the wavelength meter. We then fit individual lines to the appropriate lineshape (Lorentzian for the high-pressure data, Lorentzian convolved with Gaussian for the low-pressure data) and extracted the difference between the centers at the two pressures.

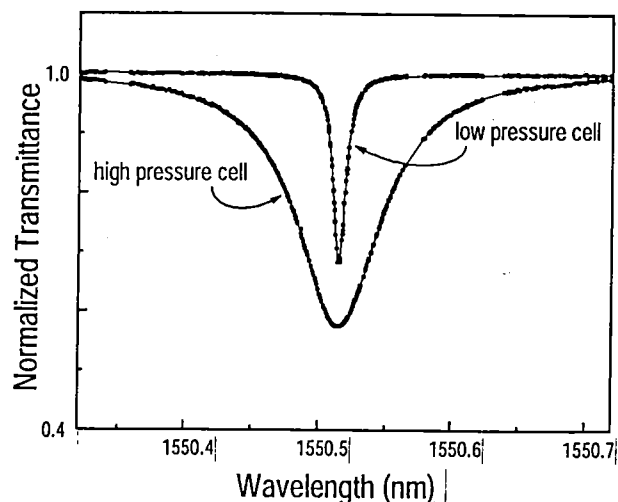


Figure 2 Scan over hydrogen cyanide line P11 showing transmission through low pressure and high pressure cells.

We found that the pressure shift in acetylene is less than 1 pm for the 27 kPa (200 Torr) SRM cell pressure and has little line dependence.³ For the acetylene SRM certification, we adjusted the literature line center values for the pressure shift and certify the wavelengths with an expanded uncertainty (coverage factor $k = 2$, that is, $\pm 2\sigma$) of ± 0.6 pm. We found that the pressure shift in hydrogen cyanide is more significant (as large as 2 pm for the SRM pressure) and has a larger line dependence. We have measured the line centers and pressure-induced shifts of 21 lines and certify their wavelengths with an expanded uncertainty of ± 0.6 pm. The

remainder of the lines in the band are certified with an expanded uncertainty of ± 3 pm, where this uncertainty is dominated by the pressure shift uncertainty.⁴ Since the cells containing the gases are sealed, environmental conditions will cause very little change in the line centers. Temperature changes will have a slight effect on the collision rate (and hence the pressure shift), but this effect is much smaller than the uncertainties quoted above for the certified line centers.

We have received inquiries about the safety of SRM 2519, since it contains a toxic gas. Each SRM unit contains about 0.5 mg of hydrogen cyanide gas. We have conducted a literature study of hydrogen cyanide toxicity and have concluded that this small amount is not a safety concern. Although cyanide (CN) is toxic at high concentrations, low concentrations are present in normal human blood; researchers estimate that normal blood cyanide levels are about 0.4 mg/l.⁵ Thus if a person were to inhale or ingest the entire contents of an SRM cell, the resultant cyanide concentration would be much less than the background level in normal human blood.

To make the line center measurements and have the capability to evaluate the SRM units, we needed a more accurate internal reference to check the accuracy of our wavelength meter. We developed a high accuracy reference based on high-resolution spectroscopy of the 780 nm rubidium $5S_{1/2}$ to $5P_{3/2}$ transition using frequency-doubled light. We amplify 1560.5 nm diode laser light using an erbium-doped fiber amplifier and frequency-double it in a periodically poled lithium niobate (PPLN) crystal. We use the resultant 780 nm light to conduct saturated absorption spectroscopy on the rubidium transitions (^{85}Rb and ^{87}Rb). The hyperfine components of these transitions are less than 10 MHz wide and their absolute frequencies have been measured with an uncertainty of ± 0.4 MHz.⁶ We used these references to calibrate our wavelength meter by stabilizing the frequency-doubled source to several different hyperfine components of the ^{87}Rb transition and comparing our wavelength meter reading to the literature values multiplied by 2. Since the lines were very narrow, the absolute stability of the locked laser was much better than the quoted wavelength meter accuracy of 1 part in 10^7 (about 20 MHz at 1560 nm). The wavelength meter reading was within 0.1 pm of the literature values for the 6 lines measured. The statistical variation of repeated measurements on the same line yielded a Gaussian distribution with a standard deviation of 0.1 pm. These measurements verify our wavelength meter accuracy; we repeat them periodically to ensure continued accuracy during SRM certification.

We are investigating other molecular references for wavelength calibration in the longer wavelength WDM region (to 1620 nm) and the 1300 nm region.

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