

Wavelength References for Wavelength Division Multiplexing

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Abstract

We describe NIST research on wavelength standards for optical fiber communications. We have developed transfer standards that can be used to calibrate instruments in the 1510–1560 nm region and are investigating references for other regions.

Introduction

Wavelength standards are needed to support wavelength division multiplexed (WDM) optical fiber communication systems operating in the 1550 nm region. It appears likely that WDM will be implemented in other wavelength regions as well, possibly covering the entire range from about 1280 to 1630 nm. Instruments such as optical spectrum analyzers, tunable lasers, and wavelength meters are used to characterize WDM system components and measure the channel wavelengths. Stable, accurately measured wavelength references can be used for single-point and scan-linearity wavelength calibration of these instruments.

Atomic and molecular absorption lines provide wavelength references that are very stable under changing environmental conditions and have well understood physical behavior. Molecules such as acetylene and hydrogen cyanide have distinctive absorption features in the 1500 nm region due to their quantized vibrational and rotational motion; these transitions are combination or overtone bands that can be probed directly. Atomic transitions in the 1300–1600 nm region are between excited states and thus require initial excitation by a laser [1] or electric discharge [2]. There is only one gas laser reference line: the 1523 nm helium-neon laser. Other atomic or molecular references can be realized by frequency doubling 1300–1600 nm light to probe atomic transitions in the 650–800 nm region [3].

We have developed moderate accuracy transfer standards that incorporate molecular gas absorption cells. These transfer standards are simple devices for calibrating instruments. We have also developed high accuracy standards for National Institute of Standards and Technology (NIST) internal calibration. The high accuracy standards are based on high-resolution spectroscopy of methane and atomic rubidium.

NIST 1510–1560 nm Transfer Standards

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 2517a), 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 better 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 SRM units are optical-fiber-coupled

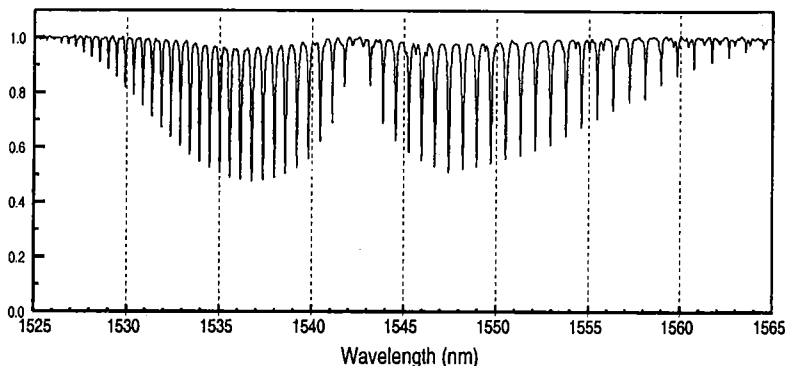


Figure 1 Hydrogen cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$) spectrum.

with singlemode 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 has sufficient purity and contains the correct gas pressure.

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 [4], and the vacuum wavelengths of the hydrogen cyanide line centers have been measured with a quoted uncertainty of 1.2×10^{-4} nm [5]. Although molecular structure is relatively insensitive to changes in environmental 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 called the "pressure shift." The line center values given in Refs. 4 and 5 are for very low pressure conditions and are applicable, at the quoted uncertainty, only to that situation. To provide sufficient 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 (6.7 kPa for acetylene, and 13.3 kPa for hydrogen cyanide). Since our goal was to certify these SRM references with an uncertainty of less than 1 pm, we measured the pressure shift for both acetylene and hydrogen cyanide.

We measured the pressure shift for 15 lines of acetylene $^{12}\text{C}_2\text{H}_2$ and found that it is less than 0.3 pm for the 6.7 kPa (50 Torr) SRM cell pressure [6]. For the acetylene SRM certification, we adjusted the literature line center values for the pressure shift and certify the wavelengths of these 15 lines with an expanded uncertainty (coverage factor $k = 2$, that is, $\pm 2\sigma$) of 0.1 pm. The remainder of the lines in the band are certified with uncertainties ranging from 0.3 to 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 variation with line number. We have measured the line centers and pressure-induced shifts of 21 hydrogen cyanide 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 [7]. 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.

High Accuracy Standards

To make line center measurements and evaluate the SRM units, we need higher accuracy internal references 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. The hyperfine components of these transitions are less than 10 MHz wide and their absolute frequencies have been measured with an uncertainty of less than 0.5 MHz [8]. 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 uncertainty of 1×10^{-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.

Figure 2 shows the methane-stabilized source we constructed as a high accuracy reference in the 1300 nm region. After optical isolation to prevent feedback, the light is split and the smaller portion (15 %) is passed through a gas absorption cell. The transmittance signal is normalized to a reference detector to remove the spectral dependence of the diode laser and isolators. The frequency-modulated laser is coarsely tuned to an absorption line. A lock-in amplifier detects the transmittance signal at the modulation frequency, creating an error signal that is proportional to the slope of the absorption line, with a zero value at line center. After gain and filtering, the correction signal is applied to the wavelength control of the laser, completing the feedback loop. The larger portion (85 %) of the split laser light is available for the calibration of laboratory equipment. We have performed a beat-note measurement with a calcium frequency standard maintained by NIST and have measured a methane transition at 1314 nm with an uncertainty of less than 5 MHz (0.03 pm). This methane-stabilized laser now serves as a NIST internal calibration reference.

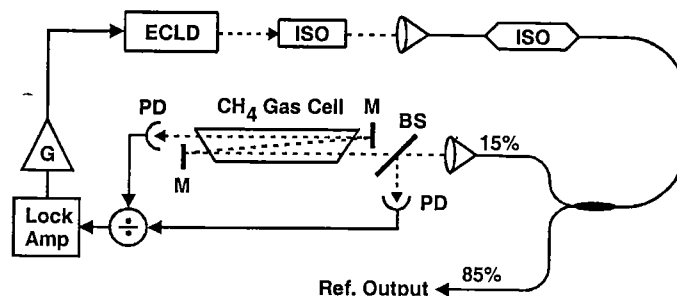


Figure 2 Setup for laser stabilization to methane: ECLD, extended cavity laser diode; ISO, isolator; BS, beamsplitter; M, mirror; PD, photodiode; G, feedback gain.

L-band Wavelength References

We examined a number of molecules as potential references in the 1560–1630 nm region. Hydrogen and deuterium halides generally have strong lines and simple spectra, but of these only hydrogen iodide (HI) [9] has spectral lines in the L-band. Unfortunately, HI has several drawbacks: the spectrum (lines between 1534 and 1595 nm) only partially covers the L-band, some of the lines have significant substructure due to the electric-quadrupole hyperfine interaction, and the gas is difficult to work with due to its reactivity and tendency to decompose. We also investigated various hydrocarbons, halogenated hydrocarbons, and other gases containing one or more CH bonds, since overtones of the CH bond's vibrational energy have spectra near 1550 nm. Although some of the spectra were in the correct location, we found that they were either too weak or highly convoluted, containing hundreds of overlapping lines. These are typically not simple linear molecules, and off-axis vibrations cause complicated spectra.

We have found that carbon monoxide provides suitable wavelength-reference absorption lines in the L-band. The carbon 12 isotope ($^{12}\text{C}^{16}\text{O}$) provides about 40 lines between 1560 and 1595 nm (see Fig. 3), and $^{13}\text{C}^{16}\text{O}$ has about 35 lines between 1595 and 1628 nm [10]. These lines are weaker than the absorption lines in either acetylene or hydrogen cyanide, but are not too weak to be considered for a portable wavelength calibration device.

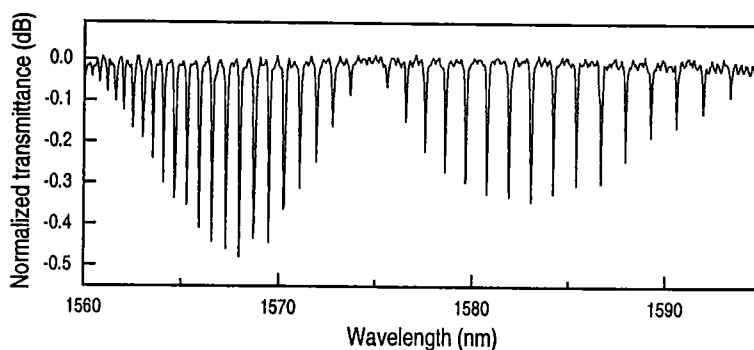


Figure 3 Carbon monoxide $^{12}\text{C}^{16}\text{O}$ spectrum

We have built a prototype wavelength SRM device based on carbon monoxide. The unit contains a 20 cm long borosilicate glass cell filled to a pressure of 133 kPa (1000 Torr). This provides lines with depths of 0.2 dB to 0.5 dB (5 % to 10 %) and widths of 0.04 nm to 0.05 nm, suitable for typical spectrum analyzer or laser calibration. The windows are fused directly to the cell body to eliminate the potential for leakage; we plan to use anti-reflection coated windows to reduce losses. Light from a singlemode optical fiber is collimated into a free beam, and then passes through the cell in a four pass re-entrant configuration. This provides a total absorption path of 80 cm inside a package with an exterior length of less than 30 cm. The

re-entrant configuration requires that the device be used with a 3 dB coupler or an optical circulator. The same packaging is suitable for either $^{12}\text{C}^{16}\text{O}$ or $^{13}\text{C}^{16}\text{O}$. We are presently investigating the pressure shift and other properties of $^{12}\text{C}^{16}\text{O}$, and plan a similar investigation of $^{13}\text{C}^{16}\text{O}$.

Conclusions

We have developed convenient transfer standards for wavelength calibration in the 1510-1560 nm region and are developing transfer standards for the 1565-1630 nm region. Since they are based on molecular absorption lines, these standards are very stable and accurate (some lines are certified with 0.1 pm uncertainty). Wavelength division multiplexing will likely expand into the 1300 and 1400 nm regions, and it will be very difficult to find absolute references for this wide wavelength range. One possibility is the use of calibrated artifact references, such as etalons [11] or fiber Bragg gratings [12]. Artifacts can provide references at arbitrary wavelengths, but they suffer from large temperature, strain, and pressure sensitivity. Passive or active thermal stabilization can substantially reduce this variability, and the artifacts can be referenced to atomic or molecular standards [11,12].

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