

# Wavelength references for 1300 nm and L-band WDM

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**Abstract:** We have surveyed potential references for 1300 nm and L-band wavelength calibration. We have developed a 1314 nm methane reference for our internal calibration and are developing a carbon-monoxide transfer standard for the 1560–1630 nm region.

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## Introduction

Future dense wavelength division multiplexing (DWDM) systems are expected to use wavelengths ranging from below 1300 nm to above 1600 nm. Wavelength calibration references are needed to characterize optical components and reliably separate densely spaced channels across this region. To complement references established at 1500 nm [1,2], we have investigated the possibilities for developing references in other regions. Wavelength references are typically based on stable, well-characterized atomic or molecular transitions, ideally with simple spectra and strong absorption lines. Historically, this has been a difficult task in these wavelength regions owing to a lack of suitable lines. Most molecular transitions are weak overtone and combination bands of infrared rotational-vibrational transitions. A few transitions are provided by atomic species, although they are usually between excited states that require some form of additional excitation. Alternatively, strong and plentiful lines in the red and near infrared can be reached by frequency doubling. Our goals are to produce high-accuracy standards for National Institute of Standards and Technology (NIST) internal calibration and moderate-accuracy transfer standards to help industry calibrate instrumentation. We discuss a number of reference materials with transitions in the 1300 nm region and our research to produce a NIST internal calibration standard. We also describe our development of Standard Reference Material (SRM) transfer standards in the 1560–1630 nm region.

## 1300 nm References

We have conducted an extensive survey of atomic and molecular reference lines in the 1280–1320 nm region. Here we briefly summarize the results of that survey and describe our work with methane.

The rubidium atom has one suitable transition at 1323.87 nm between the excited states  $5P_{1/2}$  and  $6S_{1/2}$ . This resides a little outside the desired wavelength interval, and stabilized optical pumping of the  $5P_{1/2}$  state is required. However, in one experiment a distributed feedback diode laser has been successfully locked to this transition [3]. The noble gases argon, neon, and krypton have been studied extensively as materials for stabilizing lasers in both the 1300 and 1550 nm regions [4,5]. The gases have inert physical properties and offer eight weak lines between 1280 and 1318 nm that are best probed by optogalvanic spectroscopy. Unfortunately, all the transitions occur between excited states, typically requiring an electric discharge that could slightly perturb a line's center.

Frequency doubling a 1300 nm laser allows hundreds of the visible transitions of the iodine molecule to be probed. Doppler-limited locking to iodine has been performed using an Nd:YAG laser with quasi-phase-matched lithium niobate at 1319 nm [6]. Besides efficient doubling, this scheme requires moderate heating of the iodine to populate upper states and to increase the vapor pressure.

Carbon dioxide and water are often the subject of atmospheric studies that involve both experimental spectroscopy and theoretical models [7,8]. The hundreds of lines that span the 1300 nm region are weak combinations of fundamental transitions in the infrared. Although the line strengths are about 100 times less than those of water, the spectrum of carbon dioxide is much cleaner and easier to identify. Water lines have served as spectroscopic calibrations [9,10]. We have also considered acetylene and ammonia. The strong combination lines of acetylene between 1510 and 1540 nm form a reference for C-band WDM [2], but in comparison the 69 lines between 1290 and 1306 nm are very weak [10,11]. Similarly, the lines of ammonia around 1294 nm appear to be weak, based on the long absorption path of one study [10].

While hydrogen fluoride is a rare example of a molecule with a clean and strong spectrum, there are only five lines located between 1280 and 1320 nm [12] and the molecule is highly reactive. Metal, sapphire, or plastic absorption cells with sapphire or polyethylene windows would be required. Despite this complication, the R-branch lines have been used to stabilize a diode laser [13]. By contrast, the toxic hydrogen sulfide molecule has hundreds of weak lines located in dense bands across the 1300 nm region [14]. However, only the band locations and the number of lines within them have been reported, requiring that spectra of higher resolution be collected.

Methane is an attractive reference material because of its dense spectrum, moderately strong lines, benign physical properties, and availability. The gas is neither toxic nor reactive and can be safely contained in glassware. Figure 1 shows the spectrum in a portion of the  $\nu_2 + 2\nu_3$  band of methane at a pressure of 67 kPa (500 Torr) and a 60 cm absorption length. Reducing the pressure by a factor of ten narrows the lines to  $\sim 750$  MHz in width yet maintains good absorption strength. While there are few notable features below 1310 nm, the spectrum provides increasingly complex line structure up to at least 1345 nm [9].

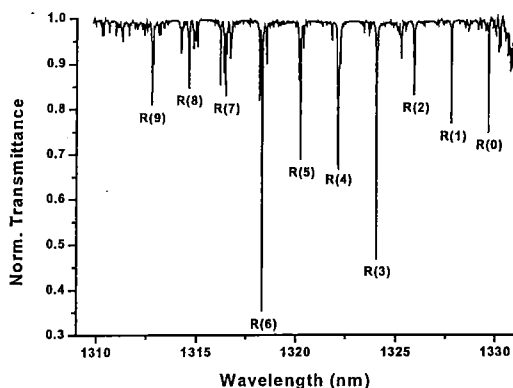


Fig. 1. Spectrum of part of the  $\nu_2 + 2\nu_3$  band of methane.

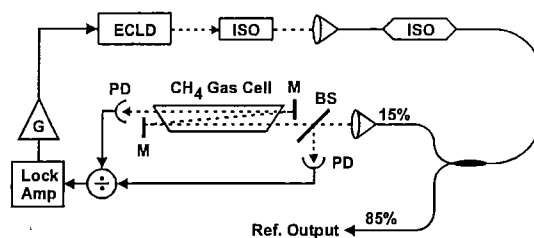


Fig. 2. Typical reference system: ECLD, extended cavity laser diode; ISO, isolator; BS, beamsplitter; M, mirror; PD, photodiode; G, feedback gain.

Figure 2 shows a methane reference source we constructed that is typical of systems that stabilize a diode laser to a gas reference material. The diode laser is tunable over the entire  $\nu_2 + 2\nu_3$  band, so a wide range of different references can be developed. 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 the 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.

### L-Band References

We examined a number of molecules as potential references in the 1560–1630 region. Hydrogen and deuterium halides generally have strong lines and simple spectra, but of these only hydrogen iodide (HI) [15] 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 electric-quadrupole hyperfine structure, 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 nm and 1595 nm (see Fig. 3), and  $^{13}\text{C}^{16}\text{O}$  has about 35 lines between 1595 nm and 1628 nm [16]. These lines are weaker than the absorption lines in either acetylene or hydrogen cyanide, but not too weak to be considered for a portable wavelength-calibration device. A

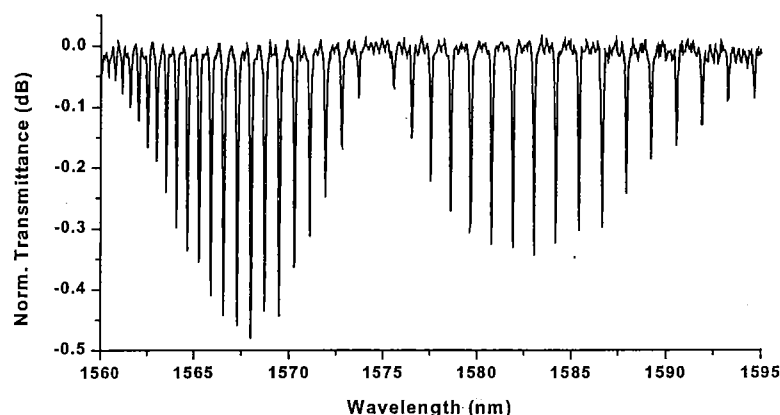


Fig. 3. Spectrum of  $^{12}\text{C}^{16}\text{O}$  at 133kPa pressure and an 80 cm absorption length.

path length of 80 cm and a pressure of 133 kPa (1000 Torr) 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. We are presently investigating the pressure shift and other properties of  $^{12}\text{C}^{16}\text{O}$ , and plan a similar investigation of  $^{13}\text{C}^{16}\text{O}$ .

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). 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  $^{13}\text{C}^{16}\text{O}$ .

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