

Wavelength accuracy in WDM: Techniques and standards for component characterization

Sarah L. Gilbert, Shelley M. Etzel, and William C. Swann

*National Institute of Standards and Technology (NIST), M/S 815.03,325 Broadway, Boulder, Colorado 80305 USA
ph. (303)497-3120, fax (303)497-7621, sgilbert@boulder.nist.gov*

Abstract: Stable, accurately measured wavelength references can be used for wavelength calibration of instruments. We discuss both fundamental and artifact wavelength calibration references and give examples of how they can be used during optical component characterization.

This paper describes work of the US Government and is not subject to US copyright.

OCIS codes: (230.1480) Bragg reflectors; (060.2300) Fiber measurements; (060.2340) Fiber optics components; (120.4800) Optical standards and testing; (300.6210) Spectroscopy, atomic; (300.6390) Spectroscopy, molecular

1. Introduction

Wavelength accuracy is an important requirement for wavelength division multiplexed (WDM) optical fiber communication systems. It appears likely that WDM will expand from the current 1530–1565 nm WDM C-band into other wavelength regions, and may ultimately cover the entire range from about 1280 to 1630 nm. Wavelength calibration references are needed for instruments such as optical spectrum analyzers (OSAs), tunable lasers, and wavelength meters that 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 instruments. There are a variety of ways to produce wavelength references, ranging from the use of fundamental atomic and molecular absorption lines to artifact references such as etalons and fiber Bragg gratings. The fundamental references can provide very accurate calibration points, but convenient references are not available in all of the wavelength regions. Artifacts, on the other hand, can provide references at arbitrary wavelengths, but they can also suffer from large sensitivity to temperature, strain, and pressure. Even with passive or active stabilization, artifact references typically offer considerably lower accuracy than fundamental references.

In this paper we discuss both fundamental and artifact wavelength calibration references and give examples of how they can be used during component characterization.

2. Fundamental References

Atomic and molecular absorption lines provide wavelength references that are very stable under changing environmental conditions. 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 can be probed directly using a broad or narrow bandwidth source. Atomic transitions in the 1300–1600 nm region are between excited states and thus require initial excitation by a laser [1] or electric discharge [2,3]. 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 [4].

The best candidates for simple calibration references are molecular absorption lines (such as acetylene and hydrogen cyanide) and emission or absorption spectra of noble gas atoms excited in an electric discharge (such as transitions between excited states of argon, krypton, neon, and xenon). The noble gas lines are typically widely spaced; for instance, Ref. 2 lists only 7 krypton lines between 1500 and 1550 nm. Unfortunately, emission lines from discharge lamps provide very low signal when coupled into optical fiber (typically 1–20 pW [5]). A higher sensitivity method is observing the optogalvanic effect (change in discharge current) due to the absorption of laser light by the atoms [2,3].

We have chosen to develop calibration references based on molecular absorption lines. Our reasons for this are twofold: molecular absorption transitions can be observed directly, without additional excitation (simplifying the design), and there are numerous absorption lines, typically spaced by 0.5 to 1 nm, providing many reference lines for scan linearity calibration. Our calibration references are NIST Standard Reference Material (SRM) transfer standards based on transitions of acetylene (SRM 2517a [6]) and hydrogen cyanide (SRM 2519 [7]). Acetylene $^{12}\text{C}_2\text{H}_2$ has more than 50 strong absorption lines in the 1510–1540 nm region. The absorption lines of hydrogen cyanide $\text{H}^{13}\text{C}^{14}\text{N}$ (Fig. 1) are better placed for current WDM C-band applications, with about 50 lines in the 1530–1565 nm region. We are currently developing SRM references for the L-band (1565–1625 nm) based on the absorption lines of carbon monoxide $^{12}\text{C}^{16}\text{O}$ (Fig. 2) and $^{13}\text{C}^{16}\text{O}$.

Although atomic and molecular structure are relatively insensitive to changes in environmental conditions, they are not completely immune, and slight shifts of line centers can occur under certain conditions. The largest potential

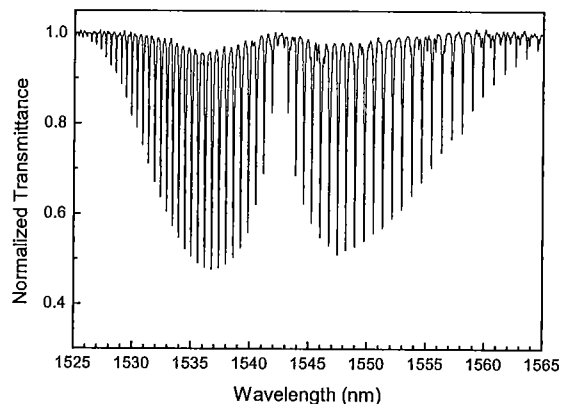


Fig. 1. Hydrogen cyanide $\text{H}^{13}\text{C}^{14}\text{N}$ spectrum. Each line in the spectrum can be used as a wavelength calibration reference.

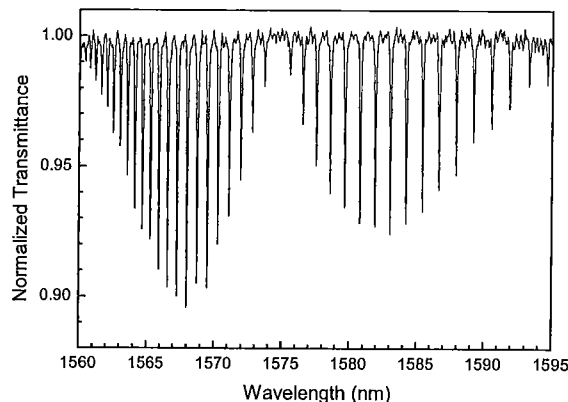


Fig. 2. Carbon monoxide $^{12}\text{C}^{16}\text{O}$ spectrum; $^{13}\text{C}^{16}\text{O}$ has a similar spectrum shifted to longer wavelength by about 35 nm.

source of line shift is due to energy level shifts caused by the interaction of the molecules during collisions. Since our goal was to certify these SRM references with an uncertainty of less than 1 pm (some of the acetylene lines are certified with an uncertainty of 0.1 pm), we measured this pressure shift for acetylene, hydrogen cyanide, and carbon monoxide, and account for the shift in the certified line center values. 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); for temperature changes of less than 50 °C, this effect is much smaller than the uncertainties quoted for the certified line centers. Each SRM unit is measured at NIST to assure that it has sufficient purity and contains the correct gas pressure.

3. Artifact Wavelength References

Artifact references, such as etalons, fiber Bragg gratings (FBGs), planar waveguide filters, or any other type of wavelength-selective filter, can be used for wavelength calibration if appropriate precautions are taken. Because the center wavelength of these devices can be very sensitive to environmental conditions (particularly temperature, strain, and pressure changes), the artifacts need to be passively or actively stabilized. The temperature dependence of narrowband filters is typically about 0.01 nm/°C (about 1 GHz/°C at 1550 nm) [8]. One approach to reducing thermally-induced variation is active temperature stabilization of the device. Passive approaches include athermal design, where the device is constructed using a combination of materials to yield reduced temperature sensitivity [8], or athermal packaging, where the device is bonded to a material that has a negative thermal expansion coefficient [9]. We are studying the stability of athermally packaged FBGs and have collected data on three gratings. We found that the center wavelength of the most stable FBG varied by less than 6 pm over 300 days, and a second grating drifted by about 7 pm over 100 days. The third FBG had a variation of less than 3 pm over a 30 day period, but then suddenly shifted 1.8 nm. In the latter case, an epoxy bonding failure was probably responsible for the large change. The variation of the other two gratings could have been due to residual temperature dependence, gradual creep of epoxy bonds, and/or polarization-dependent wavelength shift of the FBG center wavelength. We are currently investigating FBG polarization dependence.

Clearly, artifact references need to be calibrated periodically using reliable fundamental references, such as those described in section 2. Artifact references can be very effective when used to extend wavelength calibration coverage or interpolate between fundamental atomic or molecular references. The National Physical Laboratory of the UK calibrates optical spectrum analyzers using the combination of an etalon and atomic reference lines [5]. The etalon fringes serve as regular wavelength markers whose positions are determined by measuring their offsets relative to several atomic absorption lines. We are developing a hybrid wavelength reference based on superimposed FBGs stabilized to a molecular reference line [10]. Several FBGs with different center wavelengths are written at the same location in optical fiber; one of the gratings, written in the 1500 nm region, is actively stabilized to a molecular absorption line. Since the other gratings experience the same environment as the stabilized grating, they are also stable, even if the temperature or strain changes. Once these stabilized FBG wavelengths have been measured, they can be used as wavelength references. We have demonstrated a system with 1300 and 1550 nm wavelength references based on this approach, and plan to extend it to other wavelength regions.

4. Wavelength Calibration Techniques

There are a variety of ways to use wavelength calibration references to calibrate optical component characterization systems. If a system requires frequent calibration (such as some systems incorporating tunable lasers, tunable filters,

or OSAs), a wavelength reference can be used to calibrate each scan. In the case of a tunable source, a fraction of the light from the source is sent to a wavelength calibration reference and the transmittance (or reflectance, if applicable) is monitored by a separate detector, while the majority of the light is used to characterize an optical component. Thus, the wavelength scale for each scan is derived from the wavelength reference probe signal. Simple algorithms for finding peaks (or dips) can yield wavelength uncertainties in the approximate range of 10 to 50 pm (1 to 6 GHz), depending on the point density, when applied to spectra such as those shown in Figs. 1 and 2. Higher accuracy can be achieved by measuring more points over each reference line and deriving the individual line center positions using a line fitting program [6,7]. For high wavelength sweep speeds, caution should be taken to avoid or compensate signal distortion due to the filtering characteristics of detector electronics [11].

An OSA is often used with a broadband source such as an LED or fiber amplified spontaneous emission source. In this case, the wavelength calibration reference can be placed in series with the component under test, and the OSA trace will contain both the wavelength calibration information and component characteristics. Alternatively, if the OSA is sufficiently stable, wavelength calibration scans can be interleaved with component test scans. Unfortunately, OSAs can have a strong temperature dependence. Reference 12 reports an average wavelength drift of 0.012 nm/°C and found that, even in a temperature-controlled chamber, the unit required a ~2 h warmup before it stabilized. Some newer OSA units contain an internal wavelength reference such as an acetylene absorption cell.

Wavelength meters that measure a signal's wavelength relative to a built-in fundamental reference (often a helium-neon laser operating at the 632.991 nm vacuum wavelength) usually don't require frequent calibration. The most convenient way to check a wavelength meter is to measure a laser that has a known wavelength, such as the 1523.488 nm helium-neon laser (~1 part in 10⁶ absolute stability) or a laser that is stabilized to a fundamental reference. Alternatively, a tunable laser can be tuned over an absorption line while measuring the wavelength with a wavelength meter; the measured line center can then be compared with the true line center.

In all of these cases, it is important to use the wavelength of light in vacuum, rather than the wavelength in air, when calibrating equipment. The wavelength of light in air can vary substantially due to its dependence on the atmospheric pressure, temperature, and humidity.

5. Conclusions

There are a variety of convenient wavelength calibration standards in the 1500 nm region, and other standards are under development for the WDM L-band. Fundamental references based on atomic and molecular absorption or emission lines provide the highest accuracy, but they are not available in all wavelength regions. 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. Artifacts such as etalons or fiber Bragg gratings can provide references at arbitrary wavelengths, but they can suffer from large sensitivity to temperature, strain, and pressure. Passive or active thermal stabilization can substantially reduce this variability, but the artifact references need to be checked periodically against a fundamental reference. Further in the future, stabilized frequency combs may become commercially available to provide frequency (wavelength) markers throughout the WDM regions.

6. References

1. S.L. Gilbert, "Frequency Stabilization of a Fiber Laser to Rubidium: a high accuracy 1.53 μm wavelength standard," in *Frequency Stabilized Lasers and Their Applications*, Proc. SPIE 1837, 146-153 (1993).
2. Y.C. Chung, "Frequency-Locked 1.3- and 1.5- μm Semiconductor Lasers for Lightwave Systems Applications," *J. Lightwave Technol.* **8**, 869-876 (1990).
3. U. Fischer and C. von Helmolt, "Absorption Spectra of Excited Kr 84 States between 1.5 and 1.58 μm and Their Use for Absolute Frequency Locking," *J. Lightwave Technol.* **14**, 139-143 (1996).
4. A. Bruner et al., "Frequency stability at the kilohertz level of a rubidium-locked diode laser at 192.114 THz," *Appl. Opt.* **37**, 6410-14 (1998).
5. D.A. Humphreys, "Accurate wavelength calibration for optical spectrum analyzers," in *Technical Digest - Symposium on Optical Fiber Measurements*, Natl. Inst. Stnd. Technol. Spec. Publ. 905, pp. 97-100 (1996).
6. W.C. Swann and S.L. Gilbert, "Pressure-induced shift and broadening of 1510-1540-nm acetylene wavelength calibration lines," *J. Opt. Soc. Am. B* **17**, 1263-1270 (2000); S.L. Gilbert and W.C. Swann, "Acetylene ¹²C₂H₂ Absorption Reference for 1510 nm to 1540 nm Wavelength Calibration -- SRM 2517a," Natl. Inst. Stnd. Technol. Spec. Publ. 260-133 (2001 Edition).
7. S.L. Gilbert, W.C. Swann, and C.M. Wang, "Hydrogen Cyanide H¹³C¹⁴N Absorption Reference for 1530-1560 nm Wavelength Calibration -- SRM 2519," Natl. Inst. Stnd. Technol. Spec. Publ. 260-137 (1998).
8. Y. Kokubun et al., "Athermal Waveguides for Temperature-Independent Lightwave Devices," *Photon. Technol. Lett.* **5**, 1297-1300 (1993).
9. T. Iwashima et al., "Temperature compensation technique for fibre Bragg gratings using liquid crystalline polymer tubes," *Electron. Lett.* **33**, 417-419 (1997).
10. W.C. Swann et al., "Hybrid multiple wavelength reference using fiber gratings and molecular absorption," in *Proc., Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, OSA Technical Digest (Optical Society of America, Washington DC, 1999), pp. 63-65.
11. V. Bertogalli et al., "Testing passive DWDM components: uncertainties in swept-wavelength measurement systems," in *Proc., 2001 Optical Fiber Communication Conference* (Optical Society of America, Washington DC, 2001), paper THB6.
12. M. Maleki and J.C. Petersen, "Wavelength calibration of a fiber-optical spectrum analyzer: temperature dependence," *Appl. Opt.* **36**, 4451-4455 (1997).