# High-accuracy near infrared wavelength and frequency reference developments at NIST

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**Abstract:** NIST research on near infrared frequency and wavelength references is presented. A new high accuracy wavelength calibration transfer standard, SRM 2519a, based on molecular absorption lines of $H^{13}C^{14}N$ is described. Research on optical frequency combs, which are expected to enhance NIST capabilities in characterizing and disseminating frequency references, is also presented.

## Introduction

Trends in the fiber-optic communications and sensors communities create demand for ever higher accuracy near-IR wavelength and frequency references. With more complex systems, telecom component manufacturers will need to hold ever tighter spectral tolerances. Fiber-optic sensors can resolve frequency shifts of less than 100 MHz; taking advantage of this sensitivity requires calibration references with absolute accuracies better than this level. Advances of the use of photonics in biotechnology and other fields are expected to create demand for references in new wavelength regions. NIST continues to address the needs of industry through our family of molecular-absorption-based wavelength references, as well as through our thrust in developing optical frequency combs as a next-generation high accuracy frequency reference.

## NIST wavelength references

Molecular-absorption-based wavelength references offer convenient calibration standards at the 1 pm to 0.1 pm level and are robust and simple to use. Previously, we developed wavelength calibration Standard Reference Material (SRM) transfer standards for the optical fiber communications region based on acetylene (SRM 2517a, 1510–1540 nm), hydrogen cyanide (SRM 2519, 1530–1560 nm), and carbon monoxide (SRMs 2514 and 2515, 1560–1630 nm) [1]. The hydrogen cyanide $H^{13}C^{14}N$ spectrum, shown in Fig. 1, is particularly well-matched to the WDM C-band, with more than 50 strong absorption lines in the 1530–1565 nm region. We have recently upgraded the hydrogen cyanide SRM to higher accuracy;

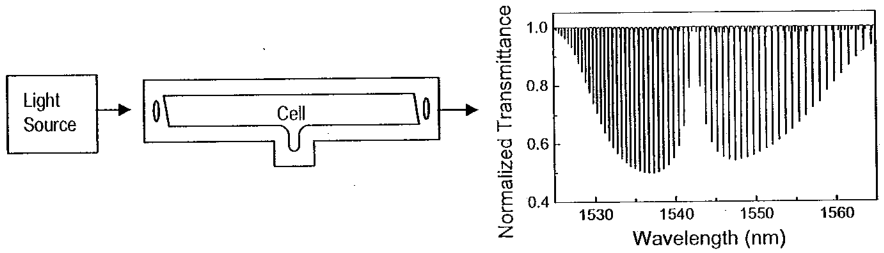

Fig. 1. Molecular absorption wavelength reference. The source may be an LED and the output spectrum displayed on a spectrum analyzer, or the source a laser tuned to a specific line and used to calibrate a wavelength meter.

SRM 2519a has line center uncertainties ($2\sigma$) as low as 0.04 pm (5 MHz) [2]. These lines were characterized at NIST using a purpose-built wavelength meter calibrated using a frequency-doubled 1560 nm laser locked to a rubidium line at 780 nm [3]. We verified the accuracy of this stabilized laser by measuring its frequency with a stabilized optical frequency comb referenced simultaneously to the NIST calcium optical frequency standard and a hydrogen maser that was calibrated by the Cs clock [4]. The uncertainties on the absorption lines, ranging from 0.04 pm to 0.24 pm, represent a practical limit of what can be obtained from a collision-broadened absorption line; pressure uncertainty, asymmetries in the line shape, and uncertainty in the wavelength meter readings caused by alignment ambiguities and air's refractive index uncertainty make obtaining lower uncertainties impractical [5,6].

## Optical frequency combs

Optical frequency combs stabilized to the primary microwave frequency standard are becoming the "de facto" optical frequency reference at national measurement laboratories [7]. Legacy laser and atomic absorption lines, until recently the mainstay primary optical frequency references, are traditionally characterized using complex spectroscopy techniques and a few established optical frequency references, making verification of candidate reference transitions difficult. Furthermore, the experimental realizations of these references often have uncertainties near 0.1 MHz. With self-referenced optical frequency combs, however, only the tooth spacing $f_r$, and the carrier envelope offset (CEO) frequency $f_{ceo}$ are needed to fully characterize the comb's frequencies. A continuous-wave (CW) laser locked to a single tooth of the stabilized comb can take the place of traditional legacy references with the advantage that the laser can be locked to the comb anywhere throughout its spectrum. Another advantage is that, since both $f_r$ and $f_{ceo}$ can be referenced to the atomic clock microwave transition, a direct path between the comb-locked CW laser and the primary clock reference is established. We discuss two technologies for calibrating wavelength or frequency reference artifacts using a variable-repetition rate frequency comb. First, we can simply lock a CW laser to a spectral feature and determine it's frequency by comparison with the comb. This method can unambiguously characterize many secondary references such narrow molecular and atomic absorption lines. Second, using the technique described below with a variable repetition rate comb, we can scan a comb-locked CW laser over a wide frequency range, enabling spectral characterization of secondary references formerly handled by a combination of a free-running tunable laser and a wavelength meter. In addition to higher accuracy and the inherent direct tie to the primary frequency standard, this technique could allow much more rapid scanning of spectral features.

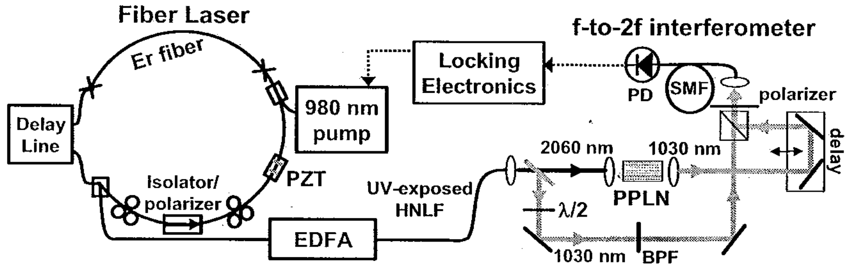

Fig 2. Tunable fiber-laser-based frequency comb and stabilization scheme. The CEO frequency is detected by a photodetector (PD), and is used to control the pump diode current. A piezoelectric (PZT) fiber stretcher in the cavity allowed for a fine adjustment of the repetition rate. The thick solid lines represent free-space optical paths, thin solid lines represent fiber optic paths, and dotted lines represent electrical paths. BPF: Bandpass filter; PPLN: Periodically-poled lithium niobate.

At NIST we have developed a near IR frequency comb based on a passively mode-locked soliton fiber laser [8] with a variable repetition rate and have demonstrated that the repetition rate can be significantly changed while the laser remains mode-locked *and* the CEO frequency remains phase-locked to a microwave reference [9]. The supercontinuum source (Fig. 2) consists of a erbium fiber ring laser, an erbium-doped fiber amplifier (EDFA), and a length of highly nonlinear fiber (HNLF) [10]. A delay line in the fiber laser cavity allows the repetition rate $f_r$ to be changed by approximately 800 kHz. The delay can be scanned quickly without any loss of mode-locking. The optical frequency of the $n^{th}$ tooth of the comb is given by the simple expression $f_n = nf_r + f_0$, where $f_r$ is the variable repetition rate and $f_0$ is the comb offset frequency, set by the CEO frequency. To detect the offset frequency, we use the self-referencing technique, which requires an octave-spanning supercontinuum. To obtain this supercontinuum, pulses from the laser are amplified and temporally compressed in the EDFA before being injected into the HNLF. The generated supercontinuum spanned from 1000 nm to 2100 nm (~157 THz wide). Self referencing is obtained by frequency doubling light from the long wavelength end of the spectrum and mixing this light with light from the short wavelength end of the spectrum to produce $f_0$.

If $f_0$ is phase-locked while the repetition rate is changed from $f_r$ to $f_r+\delta f_r$ then the $n^{th}$ comb tooth moves in frequency by $n\delta f_r$. The frequency comb expands like the bellows of an accordion, with the higher-frequency components experiencing a larger absolute frequency change. To demonstrate the variable repetition-rate frequency comb, we scanned the repetition rate of the laser over 800 kHz (corresponding to a 3 THz, or 25 nm change of a comb tooth in the 1550 nm region) by moving the in-cavity delay line. Over the course of the scan, occasional cycle slips, caused by the self referencing losing and regaining lock, occurred due to the relatively low signal-to-noise ratio of the CEO beat note. Excluding these cycle slips, the CEO frequency in a 1 s gate is phase-locked to better than a few hertz. The corresponding contribution to the instability of the optical comb frequencies is $10^{-14}$ or less, which is negligible for most applications. Locking the repetition rate scan to a frequency synthesizer, which itself can be locked to a primary microwave reference, a process we plan to undertake, would allow the scanned comb to be fully referenced.

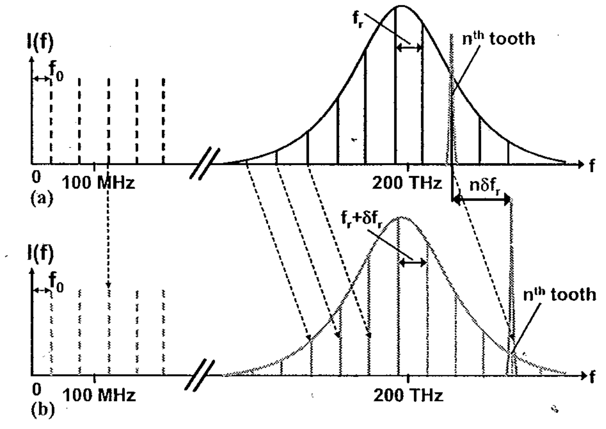

Fig. 3. Scanning a CW laser locked to the variable repetition rate frequency comb. (a) The initial frequency comb (black) with offset frequency $f_0$ and repetition rate $f_r$ where a CW laser is locked to the $n^{th}$ tooth of the comb. (b) The final frequency comb (gray) with the same offset frequency $f_0$ and a repetition rate $f_r$ that has been increased from $f_r$ to $f_r+\delta f_r$. At low frequencies (100 MHz) the shift of the comb lines are imperceptible on this scale. The CW laser is assumed to be still locked to the $n^{th}$ tooth of the comb. As a result, its frequency has been increased by $n\delta f_r$.

## Applications for frequency metrology

In the simplest configuration, a narrow feature such as a Doppler-free atomic absorption line can be characterized by locking a CW laser to the feature, and scanning the comb relative to the CW laser. Observation of the heterodyne signal between the CW laser and adjacent comb teeth allows the frequency of the CW laser, and thus the spectral feature, to be determined. Unknown laser frequencies can be determined using a similar technique. Furthermore, the frequency sweep allows unambiguous identification of an unknown laser frequency without using a wavelength meter to determine the mode number of the adjacent comb tooth [11].

A potentially more important application of the variable repetition rate laser is to scan a CW laser precisely in frequency by locking it to a single tooth of the frequency comb. If the CW laser remains locked to the $n^{th}$ comb tooth, then its frequency will also change by $n\delta f_r$, which is up to 25 nm in the 1550 nm region for our tunable comb. Figure 3 depicts a CW laser locked to the $n\sim4$ millionth tooth of a frequency comb with a fixed CEO frequency. This frequency sweep allows highly accurate scanning of very narrow features, such as Doppler-free atomic and molecular lines, and broader features such as pressure-broadened molecular absorption lines, molecular absorption bands, and etalons. Aside from removing the wavelength meter and its associated uncertainties from the spectral measurement of such features, this technique has the potential of performing scans much more rapidly. Spectral scans of molecular absorption lines performed at NIST using a purpose-built wavelength meter typically require scan times of up to 40 minutes to obtain $2\sigma$ uncertainties below the 1 MHz level. Using a variable repetition rate frequency comb, we anticipate that similar scans could be performed with lower uncertainty in less than one second. Note that a CW laser can also be scanned using a fixed frequency comb [12], but this is technically challenging because of the difficult hand-over of the phase-lock from one tooth of the comb to the next. Furthermore, a wavelength meter is initially needed to determine the CW laser's wavelength modulo the comb tooth separation.

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