**Paper**

# Developments of Optical Frequency Standards for Wavelength-division-multiplexing (WDM) Optical Fiber Communication Systems

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We have developed optical frequency standards for wavelength-division-multiplexing (WDM) optical communication systems based on absorption lines of acetylene molecules in the 1.5 μm region. We developed acetylene-stabilized diode lasers using a Doppler-free saturation absorption of acetylene as a frequency reference. We also developed an accurate frequency measurement sysytem in the 1.5 μm region and the absolute optical frequency of an acetylene line was measured with an uncertainty of 12 kHz. As a result, the acetylene optical frequency standard can be used as an accurate absolute frequency reference for the calibration of optical instruments used in the WDM systems.

**Keywords** : optical frequency standard, WDM (wavelength-division-multiplexing), optical fiber communications

## 1. Introduction

Wavelength-division-multiplexing (WDM) communication systems have been developed in order to increase the transport capacity of the present optical fiber communication. In the WDM systems, hundreds of channels are allocated at different optical frequencies or wavelengths around 1.5μm. Thus, to avoid cross talk between neighboring channels, each channel frequency should be monitored and controlled with a high accuracy. The ITU-T (International Telecommunications Unions, telecommunication standardization sector) defined the channel frequencies for the WDM system at 1.5 μm should be located on a 50 GHz grid with the reference frequency at 193.1 THz(1). In the practical WDM systems, each channel frequency should be adjusted to this grid frequency within few GHz to minimize the cross talk error. For the monitor of channel frequencies, optical spectrum analyzers and/or wavelength meters are usually used. However, the accuracy of these instruments is limited and they require accurate calibrations using atomic or molecular absorption lines as absolute frequency references. In the 1.5 μm region, several atomic and molecular transitions have been investigated for the absolute frequency references. We have investigated a Doppler-free saturation spectroscopy of weak absorption lines of acetylene molecules in the 1.5 μm region(2), and we have measured the absolute optical frequencies of acetylene lines with an uncertainty of about 100 kHz(3). As a result, highly accurate frequency references has been realized in the 1.5 μm region, and the acetylene lines have been widely used as practical frequency references for the calibration of optical spectrum analyzers and wavelength meters(4).

In order to establish accurate optical frequency standards based on the acetylene transitions in the 1.5 μm region, we have developed practical acetylene-stabilized diode lasers(5) and an accurate frequency measurement system for the absolute frequency measurement of acetylene lines together with the National Metrology Institute of Japan (NMIJ), Advanced Industrial Science and Technology(6). As a result, an acetylene transition at 1.5 μm was adopted as a new recommended radiation for the realization of meter, i.e. optical frequency (wavelength) standard by CCL (Consultative Committee for Length) in 2001. Thus the acetylene optical frequency standard will be used as an accurate and reliable frequency reference for the WDM optical communication systems in the 1.5 μm region.

In this paper, we describe the developments of acetylene-stabilized diode lasers in UEC (University of Electro-Communications) and the absolute frequency measurement of acetylene lines in NMIJ. We also discuss a traceable optical frequency standard system for the WDM optical communication systems in the 1.5 μm region.

## 2. Acetylene Frequency Reference

**2.1 Acetylene-stabilized Lasers** In 1.5 μm region, there are many rotational-vibrational absorption lines of acetylene ($C_2H_2$). As they correspond to the first overtone band transitions ($\Delta v_{C\text{-}H}=2$) of the C-H stretching vibrational mode, their absorptions strength are much weaker than those of fundamental band ($\Delta v_{C\text{-}H}=1$) in the mid-infrared region. Thus high laser intensity is needed for the Doppler-free saturation spectroscopy which enable to obtain a narrow (~MHz) frequency reference. We could realize a saturation spectroscopy of the acetylene lines at 1.5 μm using a build-up cavity technique with a low power diode laser(2). Using this method, we could stabilize the frequency of an extended cavity diode laser on a saturated absorption line of acetylene and realize accurate frequency references in the 1.5 μm region. We briefly describe our acetylene-stabilized diode laser.

The schematic diagram of our acetylene-stabilized laser is shown in Fig. 1(5). We use an extended cavity diode laser (power ~ 10 mW, linewidth ~ 100 kHz) as a light source. An acetylene absorption cell is placed inside a build-up cavity (finesse ~ 200) which enhances the intra-cavity laser intensity up to several 10 W/cm$^2$. At first, the laser frequency is locked on a resonance of the

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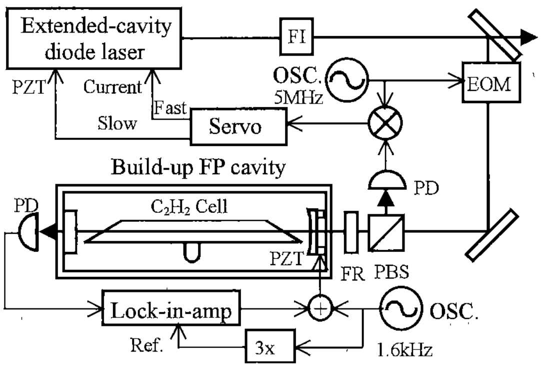


Fig. 1. Schematic diagram of an acetylene-stabilized diode laser. FI: faraday isolator, EOM: electro-optic modulator, PBS: polarization beam splitter, FR: faraday rotator, PD: photo diode, FP: Fabry-Perot

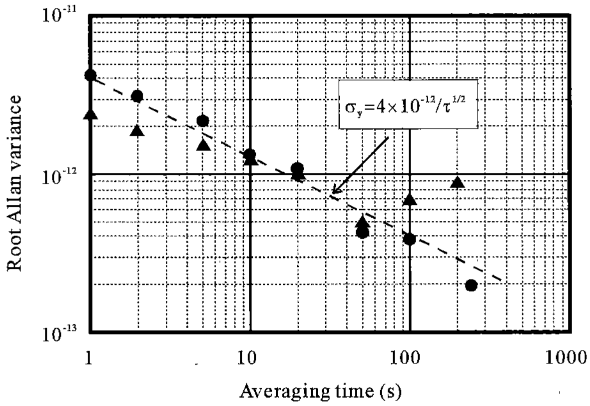


Fig. 2. Frequency stability of acetylene-stabilized diode lasers. Filled triangle: the data for a 1f demodulation, filled circle: the data for a 3f demodulation

build-up cavity using a Pound-Drever-Hall method(7), and the acetylene absorption signal is obtained by detecting the cavity transmitted light. A narrow (~ 1MHz) saturation dip is obtained at the center of the Doppler broadened acetylene absorption spectrum. Then, the cavity length is modulated at 1.6 kHz by using the piezo transducer, and the frequency error signal is extracted from the demodulation of the absorption signal at the third harmonics (3f) of the modulation frequency (f). This error signal is fed back to the cavity length, and then the laser frequency is stabilized to the center of the saturation dip of the acetylene absorption.

We prepared two sets of similar acetylene-stabilized lasers and we evaluated the frequency stability of these lasers by detecting the beat note between two lasers (Fig.2). For a comparison, the frequency stability under the feedback with a 1f demodulation was also measured (Fig. 2, filled triangle). In case of 1f demodulation, we observed small nonzero baseline in the frequency error signal and the drift of this baseline degraded the long-term frequency stability. In case of a 3f demodulation, however, the baseline drift was well suppressed and the frequency stability reached to about $2\times10^{-13}$ at the integration time of 250 s.

The frequency reproducibility of the laser was evaluated by the frequency difference between two lasers. In case of a 1f demodulation, the nonzero baseline caused the frequency offset of several 10 kHz at maximum relative to the center of the saturation dip. Whereas, in case of a 3f demodulation, the baseline offset was well reduced and the frequency difference was typically within 10 kHz ($5\times10^{-11}$).

**2.2 Transportable Laser and Frequency Comparison**

Similar acetylene-stabilized lasers were also developed at NMIJ, and they showed similar performances in the frequency stability and reproducibility(8). Thus we attempted to compare the frequency between the UEC acetylene-stabilized lasers and the NMIJ lasers. Such a frequency comparison is important for the evaluation of frequency reproducibility including systematic frequency shift between two systems.

We developed a compact transportable acetylene-stabilized laser which was composed on an aluminium optical bread board of the size 45 cm × 30 cm. The servo electronics were same as that used in our previous lasers. At first, we compared the frequency between the transportable laser and the previous laser in UEC. Both lasers were stabilized on a same acetylene transition ($^{13}C_2H_2$ P(16)) and we measured the beat frequency between them using an acousto-optic modulator (AOM) as a frequency shifter. We confirmed that the frequency difference was within 10 kHz. Then we transported this transportbale laser to NMIJ in Tsukuba from UEC in Tokyo. Both lasers were also stabilized on a same acetylene transition ($^{13}C_2H_2$ P(16)), and we compared the frequency between them. As a result, the frequency difference was also measured to be within 10 kHz. Thus we could conclude that the frequency reproducibility of our acetylene-stabilized lasers was on the order of 10 kHz ($5\times10^{-11}$). Further evaluation of the frequency reproducibility should include the pressure shift and light shift. The pressure shift of 1.5 μm acetylene transitions was reported at rather high pressure (> 1000 Pa )(4), and it was estimated to be about −10kHz for our acetyelene absorption cells at low pressure (4 Pa). As the UEC and NMIJ lasers used the same acetyelne cell with same pressure (4 Pa), the frequency difference due to the pressure shift was estimated to be kHz order.

## 3. Absolute Frequency Measurements of Acetylene Transitions

**3.1 First Frequency Measurements** The absolute optical frequencies of acetylene transitions in the 1.5 μm region were measured by us for the first time in 1995(3). In this previous measurement, we first determined the absolute optical frequency of a HCN transition at 1.556 μm using a Rb two-photon transition ($^{87}$Rb $5S_{1/2}$-$5D_{3/2}$) at 0.778 μm as an absolute frequency reference(9). Then we measured the frequency differences up to 2 THz between this HCN transition and the acetylene transitions around 1.54 μm using an optical frequency comb generator(3),(10). As a result, the absolute optical frequencies of ninty transitions of acetylene and its isotope molecules ($^{12}C_2H_2$, $^{13}C_2H_2$) were determined with an frequency uncertainty of about $10^{-9}$ (or 200 kHz), which was mainly limited by the frequency uncertainty and reprodicibility of the HCN stabilized laser(9). Since then, these 1.5 μm acetylene transitions can be used as absolute frequency (or wavelength) references for the calibration of the optical instruments used in the WDM systems(4).

**3.2 Accurate Frequency Measurement System in the 1.5 μm Region** To establish accurate optical frequency standards in the 1.5 region based on these acetylene transitions, we have further improved the accuracy in the frequency measurments of acetylene transitions. We have developed a new frequency

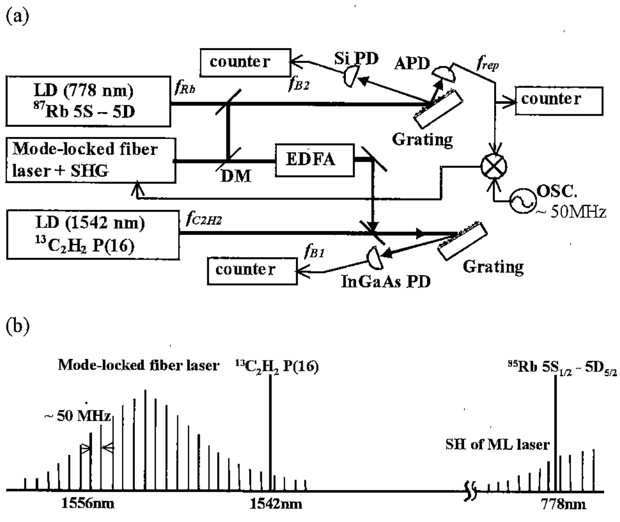


Fig. 3. (a) Schematic diagram of the frequency measurement system. LD: laser diode, DM: dichroic mirror, EDFA: Er-doped fiber amplifier, SHG: second harmonic generation, APD: avalanche photo diode. (b) The frequency link between the acetylene and the reference Rb transitions

measurement system for the 1.5 μm acetylene transitions at NMIJ[6]. In this new system, we realized a direct frequency link between the acetylene transitions around 1.54 μm and a reference Rb two-photon transition at 0.778 μm using a two-color mode-locked fiber laser[6].

The schematic diagram of this frequency measurement system is shown in Fig. 3. We use a commercial mode-locked (ML) fiber laser (IMRA Inc. Femtolite C-20-SP) with both fundamental (1.56 μm) and second-harmonic (0.78 μm) outputs. The fundamental and second harmonic outputs are separeted by using a dichroic mirror, and they are mixed with an acetyene-stablized laser and a Rb two-photon reference laser, respectively. The beat signals at both 1.54 μm and 0.778 μm are detected by photo diodes and these beat frequencies $f_{B1}$ and $f_{B2}$ are measured by using electroric counters. The repetetion rate of the ML laser $f_{rep}$ is about 50MHz and it is stablized to the stable RF synthesizer frequency by controlling the cavity length of the fiber laser. The frequency of the acetylene-stabilized laser $f_{C2H2}$ is given by, $f_{C2H2} = (f_{Rb} \pm f_{B2} + m \times f_{rep})/2 \pm f_{b1}$,, where $f_{Rb}$ is the frequency of the Rb-stabilized laser, and $m$ is the integer. As the acetylene transition frequency $f_{C2H2}$ has been already known with an uncertainty of about 200 kHz from our previous measurement[3], the integer $m$ could be exactly determined. Thus the new value of $f_{C2H2}$ could be determined from the measured beat frequencies $f_{b1}$, $f_{b2}$ and $f_{rep}$ with an statistical uncertainty of kHz order.

**3.3 Calibration of Absolute Frequency** In the new frequency measurement system, the frequency accuracy is mainly determined by the absolute frequency accuracy of our reference Rb-stabilized laser. The absolute optical frequency of the reference Rb two-photon transition ($^{85}$Rb $5S_{1/2}$–$5D_{5/2}$) was measured with an uncertainty of about $10^{-11}$ by using a frequency chain at LPTF (Laboratoire Primaire du Temps et des Frequences) in Paris[11]. Thus we calibrated the absolute optical frequency of our Rb-stablized laser by the international frequency comparison. A Rb-stabilized laser developed at LPTF was brought to NMIJ and the frequency comparison between them was made at NMIJ. As a result, the absolute optical frequency of our Rb-stabilized laser was determined with an unceratinty of about 2 kHz[12]. The resettability of our Rb-stabilized laser was also evaluated and it was about several kHz.

Recently, a direct frequency link between an optical and a microwave frequency can be realized by using a a self referring femto-second optical frequency comb[13]. Using this new method, an optical frequency in the near infrared and visible region can be measured with an accuracy of that of a reference microwave frequency standard. Thus we measured the absolute optical frequency of our Rb-stabilized laser using this method[14]. The detail of this method was described previously[13][14]. The spectrum of a femto-second mode-locked (ML) Ti-saphire laser around 0.8 μm is broadened to more than an octave (0.5 μm – 1.1 μm) by using a self phase-modulation effect in a photonic structure non-linear optical fiber. The repetetion rate of the ML laser is stabilized to a microwave frequency standard. By frequency doubling the long wavelength portion (~ 1 μm) of the spectrum and comparing it to the short wavelength portion ( ~ 0.5 μm), the absolute optical frequency of each mode of the output spectrum is determined[13][14]. By measuring the beat frequency between our Rb-stabilized laser and one of the ML output mode, we could determined the absolute optical freuquency of our Rb-stabilized laser. As a result, the measured frequency was about 12 kHz lower than that determined from the international comparison. Considering that we could not identyfy the origin of this frequency deviation between both measurements, we determined the absolute optical frequency of our Rb-stabilied laser as the mean value of both frequency measurements. Using the final value for our Rb reference frequency, we could determine the absolute optical frequency of an acetylene transition $^{13}C_2H_2$ P(16) ($\lambda$=1.5423837 μm) as 194 369 569 385 kHz with an uncertainty of 12 kHz or $6\times10^{-11}$. The new value coincided with the previous value within 5 kHz, and the frequency uncertainty was reduced to 12 kHz which was one order smaller than that in the previous measurement.

## 4. Optical frequency Standard for WDM Optical Communications

Based on the result of new accurate frequency measurement of acetylene transitions[12], we proposed acetylene transitions as optical frequency standards in the 1.5 μm region, and one acetylene transition was adopted as a new recommended radiation for the definition of the meter by CCL in 2001. The adopted acetylene optical frequency standard is as follows[15];

Absorbing molecule: $^{13}C_2H_2$,
Transition: $\nu_1+\nu_3$ P(16),
Frequency: 194369569.4 MHz,
Wavelength: 1.542 383 712 μm,
Provisional uncertainty: $5\times10^{-10}$ (0.1 MHz),
Acetylene pressure: 1.3 – 5.3 Pa.

As a result, this acetylene optical frequency standard can be used as a highly accurate absolute frequency reference for the 1.5 μm WDM systems. For a reliable frequency management, it is important to realize a SI (the International System of Units) traceable frequency standard system (Fig. 4).

In the practical WDM communication systems with a 50 or 100 GHz grid spacing, the frequencies of laser sources and filters should be maintained to coincide with the ITU grid frequencies with an accuracy of about $10^{-5}$ (~2GHz) by using frequency (or

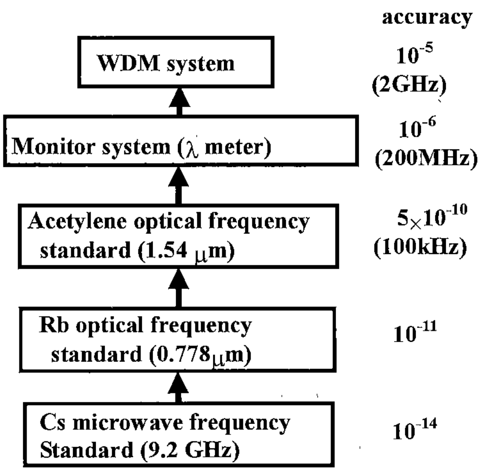


Fig. 4. Traceable optical frequency standard for the 1.5 μm WDM systems

wavelength) monitor systems. As the measurement accuracy of typical wavelength (λ) meters is about $10^{-6}$ (or 200 MHz), they are used as the monitor systems. However, the wavelength meters have systematic measurement errors and they require absolute wavelength calibrations. Thus the acetylene optical frequency standard can be used as an absolute wavelength reference with an accuracy of $5\times10^{-10}$ (or 100 kHz) for the calibration of these wavelength meters. This frequency accuracy is high enough for the future dense WDM systems with a narrower channel spacing of 25 GHz or 12.5 GHz. This acetylene optical frequency standard can be also calibrated by using a Rb optical frequency standard at 0.778 μm with an accuracy of $10^{-11}$. The Rb optical frequency standard can be finally calibrated by using a cesium (Cs) atomic clock at 9.2 GHz which defines the frequency. Thus, as long as this traceability chain is maintained, a highly accurate frequency management in the WDM systems will be realized for long years.

## 5. Summary

We have developed acetylene optical frequency standards for the WDM optical communication systems in the 1.5 μm region. We have described the performance of the acetylene-stabilized laser and the absolute frequency measurements of acetyelene transitions. A traceable optical frequency standard system in the 1.5 μm region is now available and it will contribute a reliable frequency management in the WDM optical communications.

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## References


(1) ITU-T Recommendation G 692 : Optical Interfaces for multichannel systems with optical amplifiers (1998)

(2) M. de Labachelerie, K. Nakagawa, and M Ohtsu : "Ultra–narrow $^{13}C_2H_2$ saturated absorption lines at 1.5 μm", *Opt. Lett.*, Vol.19, pp.840-842 (1994)

(3) K Nakagawa, M. de Labachelerie, Y. Awaji, and M. Kourogi · "Accurate optical frequency atlas of 1.5 μm band of acetylene", *J. Opt. Soc. Am. B*, Vol 13, pp.2708-2714 (1996)

(4) 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*, Vol.17, pp.1263-1270 (2000)

(5) K. Nakagawa and A. Onae . "Development of an Acetylene Optical Frequency Standard at 1.5 μm and its Applications", Proc. of SPIE Vol.4269, p 41-49 (2001)

(6) A. Onae, T. Ikegami, K. Sugiyama, F.-L. Hong, K. Minoshima, H. Matsumoto, K Nakagawa, M. Yoshida, and S Harada : "Optical frequency link between an acetylene stabilized laser at 1542nm and an Rb stabilized laser at 778nm using a two-color mode-locked fiber laser", *Opt. Commun*, Vol.183, pp.181-187 (2000)

(7) R. W. P. Drever, J. L. Hall, F. V. Kowalski, J Hough, G M Ford, A. J. Munley, and H. Ward : "Laser phase and frequency stabilization using an optical resonator", *Appl. Phys. B*, Vol 31, pp 97-105 (1983)

(8) A Onae, K. Okumura, J. Yoda, K. Nakagawa, A. Yamaguchi, M. Kourogi, K. Imai, and B. Widiyatomoko "Toward an Accurate Frequency Standard at 1 5 μm Based on the Acetylene Overtone Band Transition", IEEE IM48, pp.563-566 (1999)

(9) Y. Awaji, K Nakagawa, M. de Labachelerie, M Ohtsu, and H. Sasada : "Optical frequency measurement of the HCN Lamb-dip-stabilized 1.5 μm diode laser", *Opt. Lett*, Vol.20, pp.2024-2026 (1995)

(10) M. Kourogi, K. Nakagawa, and M. Ohtsu : "Wide-Span Optical Frequency Comb Generator for Accurate Optical Frequency Measurement", *IEEE J. Quantum Electron.*, Vol.29, pp.2693-2701 (1993)

(11) D. Touahri, O. Acef, A. Clairon, J.-J. Zondy, R Felder, L. Hilico, B. de Beauvoir, F. Biraben, and F. Nez · "Frequency measurement of the $5S_{1/2}(F=3)-5D_{5/2}(F=5)$ two-photon transition in rubidium", *Opt. Commun.*, Vol.133, pp.471-479 (1997)

(12) A. Onae, K. Okumura, K. Sugiyama, F. L. Hong, H. Matsumoto, K. Nakagawa, R. Felder, and O. Acef . "OPTICAL FREQUENCY STANDARD AT 1 5 μm BASED ON DOPPLER-FREE ACETYLENE ABSORPTION", Proc. of the 6th Symposium of FREQUENCY STANDARDS AND METROLOGY, World Scientific, pp. 445-452 (2002)

(13) S. A. Diddams, D J Jones, J. Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S Windeler, R. Holzwarth, Th.Udem, and T. W. Hänsch : *Phys. Rev. Lett.* Vol 84, pp.5102-5105 (2000)

(14) K. Sugiyama, A. Onae, F. -L. Hong, H. Inaba, S. N. Slyusarev, T. Ikegami, J. Ishikawa, K. Minoshima, H Matsumoto, J. C. Knight, W. J Wadsworth, and P. St. J Russel : "OPTICAL FREQUENCY MEASUREMENT USING AN ULTRAFAST MODE-LOCKED LASER AT NMIJ/AIST", Proc. of the 6th Symposium of FREQUENCY STANDARDS AND METROLOGY, World Scientific, pp. 427-434 (2002)

(15) T. J. Quinn . *Metrologia*, Vol 40, pp.103–133 (2003)



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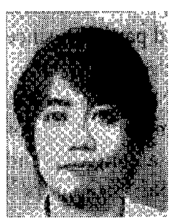

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