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

Ken'ichi Nakagawa*  Member
Atsushi Onae**  Non-member

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 system 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 Union, 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 (C2H2). As they correspond to the first overtone band transitions (ΔυC-H=2) of the C-H stretching vibrational mode, their absorptions strength are much weaker than those of fundamental band (ΔυC-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(7). 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(8). 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/cm2. At first, the laser frequency is locked on a resonance of the

* Institute for Laser Science, University of Electro-Communications 1-3-1 Chofugaoka, Chofu 182-8585
** National Metrology Institute of Japan, Tsukuba Central 3 1-1-1 Umezono, Tsukuba 305-8563
Developments of Optical Frequency Standard

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 broadening 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 2×10⁻¹⁵ 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 (5×10⁻¹⁴).

2.2 Transportable Laser and Frequency Comparison

Similar acetylene-stabilized lasers were also developed at NMJ, and they showed similar performances in the frequency stability and reproducibility(6). Thus we attempted to compare the frequency between the UEC acetylene-stabilized lasers and the NMJ 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 (C₂H₃, 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 transportable laser to NMJ in Tsukuba from UEC in Tokyo. Both lasers were also stabilized on a same acetylene transition (C₂H₃, 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 (5×10⁻¹⁴). 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)() and it was estimated to be about ~10kHz for our acetylene absorption cells at low pressure (4 Pa). As the UEC and NMJ lasers used the same acetylene 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(). 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 (⁸⁷Rb 5S_{1/2}→5D_{3/2}) at 0.778 μm as an absolute frequency reference(). 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().

As a result, the absolute optical frequencies of ninety transitions of acetylene and its isotope molecules (⁸⁷C₂H₃, ¹³C₂H₃) were determined with an frequency uncertainty of about 10⁻⁸ (or 200 kHz), which was mainly limited by the frequency uncertainty and reproducibility of the HCN stabilized laser(). 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().

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 measurements of acetylene transitions. We have developed a new frequency
measurement system for the 1.5 µm acetylene transitions at NMJ(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 separated by using a dichroic mirror, and they are mixed with an acetylene-stabilized laser and a Rb two-photon reference laser, respectively. The beat signals at both 1.54 µm and 0.778 µm are detected by photodiodes and these beat frequencies \( f_{b1} \) and \( f_{b2} \) are measured by using electronic counters. The repetition rate of the ML laser \( f_{rep} \) is about 50 MHz and it is stabilized to the stable RF synthesizer frequency by controlling the cavity length of the fiber laser. The frequency of the acetylene-stabilized laser \( f_{c2012} \) is given by, 
\[
f_{c2012} = (f_{b1} \pm f_{b2} + m \times f_{rep})/2 \pm f_{s10},
\]
where \( f_{s10} \) is the frequency of the Rb-stabilized laser, and \( m \) is the integer. As the acetylene transition frequency \( f_{c2012} \) has been already known with an uncertainty of about 200 kHz from our previous measurement(6), the integer \( m \) could be exactly determined. Thus the new value of \( f_{c2012} \) can 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 optical frequency of the reference Rb two-photon transition \( ^{85}\text{Rb} \, 5S_{1/2} \rightarrow 5D_{3/2} \) was measured with an uncertainty of about 10\(^{-11} \) by using a frequency chain at LPTF (Laboratoire Primaire du Temps et des Fréquences) in Paris(10). Thus we calibrated the absolute optical frequency of our Rb-stabilized laser by the international frequency comparison. A Rb-stabilized laser developed at LPTF was brought to NMJ and the frequency comparison between them was made at NMJ.

As a result, the absolute optical frequency of our Rb-stabilized laser was determined with an uncertainty of about 2 kHz(12). The resubbility 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 self-referencing femtosecond 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(6). The detail of this method was described previously(3,4,14). The spectrum of a femtosecond mode-locked (ML) Ti:sapphire 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 crystal non-linear optical fiber. The repetition 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(3,14). By measuring the beat frequency between our Rb-stabilized laser and one of the ML output mode, we could determine the absolute optical frequency 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 identify the origin of this frequency deviation between both measurements, we determined the absolute optical frequency of our Rb-stabilized 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 \(^{13}\text{C}_2\text{H}_2\) P(16) (\( \lambda = 1.5423837 \) µm) as 194 369 569 385 ± 1 kHz with an uncertainty of 12 kHz or \( 6 \times 10^{-11} \). 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 our 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(13):

Absorbing molecule: \(^{13}\text{C}_2\text{H}_2\).
Transition: \( v_1 + v_4 \) P(16),
Frequency: 194369569.4 MHz,
Wavelength: 1.542 383 712 µm,
Provisional uncertainty: \( 5 \times 10^{-10} \) (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 \( 10^{-6} \) (~2GHz) by using frequency (or
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 $5 \times 10^{-10}$ (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 also be calibrated by using a Rubidium optical frequency standard at 0.778 μm with an accuracy of $10^{-11}$. The Rubidium 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 acetylene 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.

(Manuscript received April 4, 2003, received Aug. 29, 2003)

References


Ken’ichi Nakagawa (Member) was born in Kanagawa, Japan, on December 20, 1961. He received the B.S., M.S., and Ph.D. degrees in physics from the University of Tokyo, Tokyo, Japan, in 1984, 1986, and 1989, respectively. He joined Tokyo Institute of Technology as a research associate in 1989. He joined Tokyo Institute of Polytechnics as a lecturer in 1995 and became an associate professor in 1997. In 1998, he joined Institute of Laser Science, University of Electro-communications as an associate professor. His research interests are laser cooling of neutral atoms, Bose-Einstein condensation, atom interferometry, optical frequency standard. He is a member of the Physical Society of Japan, the Japan Society of Applied physics, the Laser Society of Japan, the Institute of Electrical Engineers of Japan, and the Optical Society of America.

Atsushi Onae (Non-member) was born in Tokyo, Japan, in 1958. He received the B.S., M.S., and Ph.D. degrees in physics from the University of Tokyo, Tokyo, Japan, in 1982, 1985, and 1990, respectively. He joined National Research Laboratory of Metrology (NRLM), tsukuba, Japan, in 1988. From 1993 to 1994, he joined the Max-Planck-Institute fuer Quantenoptik, Munchen, Germany, as a visiting scholar supported by the Science and Technology Agency of Japan. He is currently a group leader of the wavelength standard section at the Advanced Institute of Science and Technology (AIST), and is engaged in the laser spectroscopy and laser frequency measurement. He is a member of the Physical Society of Japan, the Japan Society of Applied physics.