DEVELOPMENT OF OPTICAL FREQUENCY STANDARDS IN THE 1.5 MICRON REGION FOR WDM OPTICAL COMMUNICATION SYSTEMS

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ABSTRACT

We have developed frequency-stabilized diode lasers based on the overtone band transitions of acetylene molecules in the 1.5 micron region. The frequency stability and reproducibility of the acetylene-stabilized lasers is about 2×10^{-13} and 10^{-10}, respectively. The absolute frequencies of acetylene transitions have been determined with an uncertainty of about 10^{-10} using a Rb two-photon transition at 778nm as an absolute frequency reference. As a result, the acetylene transition ($^{13}C_2H_2$ P(16)) was recently established as a new optical frequency (wavelength) standard. The acetylene optical frequency standards can be used as accurate and practical optical frequency (or wavelength) references for the WDM (wavelength-division-multiplexed) optical communication systems and optical measurement instruments in the 1.5 micron region.

INTRODUCTION

Optical frequency standards in the 1.5 micron optical fiber communication bands have been needed for the wavelength-division-multiplexed (WDM) communication systems. In the WDM system, the optical frequency of each channel should be precisely controlled in order to avoid cross talk between neighboring channels. The ITU (International Telecommunications Union) defined that the channel frequencies should be located on a 50 GHz frequency grid centered at 193.1 THz [1]. For the frequency (or wavelength) calibration of optical spectrum analyzers or wavelength meters, the absolute frequency references with an accuracy of 10^{-8} or better are needed in the 1.5 micron region. We have developed optical frequency standards in this 1.5 micron region based on the overtone band transitions of acetylene and its isotope molecules [2,3]. Using Doppler-free saturated absorption of acetylene transitions as a reference, we have realized acetylene-stabilized diode lasers with high frequency stability (2×10^{-13}) and frequency reproducibility ($\sim10^{-10}$) [3]. The absolute frequencies of acetylene transitions have been determined with an accuracy of about 10^{-9} using an rubidium (Rb) two-photon transition at 778 nm as an absolute frequency reference, and we have realized an accurate frequency atlas of acetylene in the 1.5 micron region including total 90 absorption lines of both $^{12}C_2H_2$ and $^{13}C_2H_2$ [2]. Based on this accurate frequency atlas of acetylene, wavelength calibration transfer standards using high pressure Doppler-broadened absorption of acetylene was recently developed for the calibration of relatively low resolution instruments [4].

Based on these preceding investigations, we have developed practical optical frequency standards for the accurate frequency definition and calibration for the WDM fiber communication systems in the 1.5 micron region [5]. We have also developed a new frequency measurement system which directly links between acetylene transitions and a reference Rb two-photon transition at 778nm in order to improve the frequency accuracy of the acetylene transitions [6][7]. Accordingly, the acetylene transition ($^{13}C_2H_2$ P(16)) was adopted as one of the new recommended radiation by the Consultative Committee for Length (CCL) in 2001.

ACETYLENE-STABILIZED OPTICAL FREQUENCY STANDARD LASER

We have developed acetylene-stabilized diode lasers using a saturation spectroscopy with a build-up cavity [2,3]. These laser were described in detail in Refs.[3,5]. Here we briefly describe our laser system (Fig. 1). The laser source is an extended-cavity diode laser with an output power of 10mW. A sealed-off absorption cell filled with acetylene ($^{12}C_2H_2$ or $^{13}C_2H_2$) gas at low pressure (4 Pa) is put into the build-up Fabry-Perot cavity with a finesse of about 150. The laser is first locked to the build-up cavity using a Pound-Drever-Hall method [8], and then the laser is locked on the saturation dip of the acetylene absorption by dithering the cavity length. In order to reduce the nonzero offset in the frequency discrimination signal, we use a third-harmonic lock-in detection method [5]. A frequency stability reaches 2×10^{-13} at the averaging time of 200 s, and the frequency reproducibility is typically within about 5 kHz [5].

We have also developed portable acetylene-stabilized lasers for the practical applications [5]. The whole optical system is composed on the optical breadboard (45 cm x 30 cm) (Fig. 2).

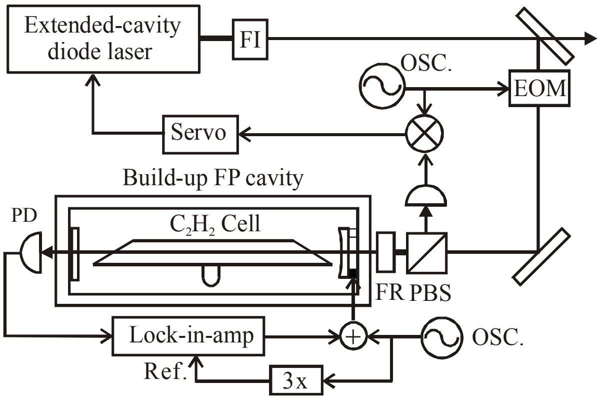

Fig.1 Schematic diagram of the acetylene-stabilized laser.

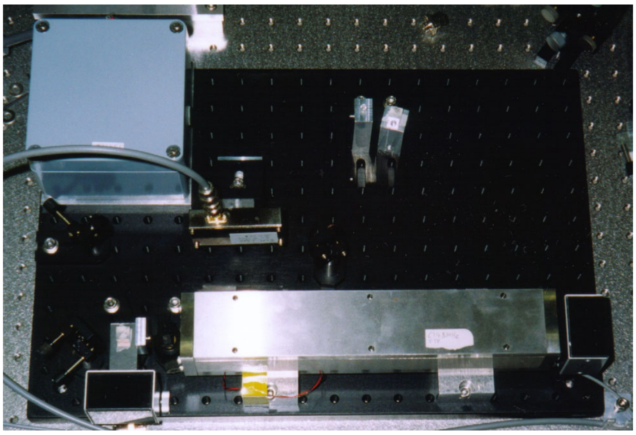

Fig.2 Portable acetylene-stabilized diode laser.

ABSOLUTE FREQUENCY MEASUREMENTS

In order to determine the absolute optical frequency of acetylene transitions, the direct frequency link between the acetylene transitions at 1.5 μm and a reference Rb two-photon transition at 778 nm has been developed at NMIJ (National Metrology Institute of Japan, former NRLM)[6,7,9]. Using a two-color (1560nm, 780nm) mode-locked Er-doped fiber laser, the optical setup for the frequency link was largely simplified (Fig. 3) [6]. By stabilizing the repetition rate of the mode-locked fiber laser, we could reduce the measurement error to the kHz level (~ 10^{-11}) [7].

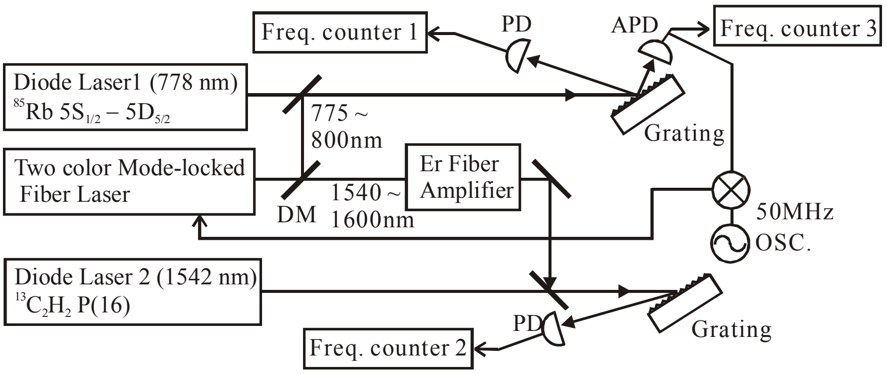

Fig. 3 Schematic diagram of the frequency measurement system.

The remaining problem was the frequency accuracy of our reference Rb-stabilized laser. We calibrated the absolute frequency of our Rb-stabilized laser by the international frequency comparison with a Rb-stabilized laser of BNM-LPTF [7,10]. As a result, the absolute frequency of our Rb-stabilized laser was determined with an uncertainty of about 2 kHz or $5x10^{-12}$. Using a recently developed femtosecond Ti:sapphire mode-locked laser frequency comb [11,12], we also independently measured the absolute frequency of our Rb-stabilized laser with a uncertainty of about several kHz [7], but the measured frequency was 12 kHz lower than that determined from the international comparison. Thus we concluded the absolute frequency of our Rb-stabilized laser was assumed to be the mean frequency between two. Using this calibrated Rb frequency and considering the reproducibility of acetylene stabilized lasers, we finally determined the absolute frequency of an acetylene transition ($^{13}C_2H_2$ P(16)) to be 194 369 569 385(12) kHz (Fig. 4).

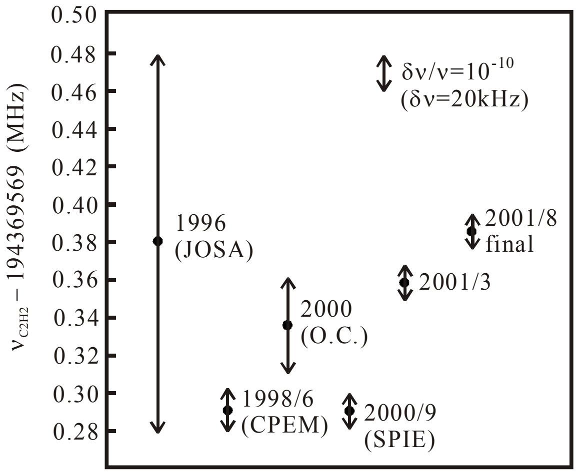

Fig.4 Optical frequency measurements of acetylene transition ($^{13}C_2H_2$). JOSA; ref.[1], CPEM; ref.[8], O.C.; ref. [6], final ; ref.[7].

Considering these results, the Consultative Committee for Length (CCL) recently adopted the acetylene transition ($^{13}C_2H_2$ P(16)) as the new recommended radiation for the realization of the definition of the metre. The adopted frequency is 194 369 569.4 MHz with a provisional uncertainty of 100 kHz. Thus this acetylene transition will be used as an authorized optical frequency standard in the 1.5 micron region. Other many acetylene transitions can be also used as an enough accurate absolute frequency reference with an uncertainty of 100 kHz or below, and these acetylene transitions can cover the wavelength region from 1520 nm to 1550 nm.

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