

Saturated Absorption Spectroscopy of $^{13}\text{C}_2\text{H}_2$ in the Near Infrared Region

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(Received February 19, 2004)

Using the external cavity spectroscopy method, we have observed the saturated absorption spectrum of the P(16) line of the $\nu_1+\nu_3$ band of $^{13}\text{C}_2\text{H}_2$. The frequency of a laser has been stabilized to the saturated absorption spectrum. The relative contrast of the saturation spectrum is about 7% with respect to the linear absorption and the linewidth is about 1.8 MHz. The frequency fluctuation of the stabilized LD is about ± 20 kHz for a sampling time of 100 ms.

OCIS codes : 300.6460, 300.6260, 060.4510

I. INTRODUCTION

The near infrared region of a frequency-stabilized laser diode has attracted strong interest for its potential applications in optical communication systems such as DWDM (Dense Wavelength Division Multiplexing), fiber sensors, high-resolution spectroscopy, and optical frequency standards. The vibrational-rotational transitions of molecules such as C_2H_2 and HCN have a large number of well-spaced resonances in the 1.5 μm region. However, due to the low electric-dipole moment associated with the acetylene vibrational-rotational transition ($\mu \cong 3 \times 10^{-3}$ Debye), it is difficult to obtain a saturated absorption spectrum for these molecular transitions.

In 1994, De Labachellerie et. al. overcame this problem and detected these weak molecular saturated absorption lines using external-cavity spectroscopy [1-3]. The external-cavity technique increased the detection sensitivity and built up intercavity power through the use of an external optical resonator. This technique allowed the use of low-power lasers for the input, even for weak transitions requiring large intensities for sub-Doppler high-resolution saturation spectroscopy [1-2]. In 1995, Nakagawa et. al. demonstrated precise optical frequency-difference measurement of acetylene absorption lines at 1.5 μm using an optical comb generator [4,5]. In 1997, Onae et. al. observed the saturated absorption spectrum of the $\nu_1+\nu_3$ band of $^{13}\text{C}_2\text{H}_2$ using an extended cavity laser diode and EDFA (erbium doped fiber amplifier) [6]. Other groups have actively studied the optical frequency standards in the 1.5 μm region [7-11].

Recently, CCL (Comité Consultatif de la Longueur) of CIPM (Comité International des Poids et Mesures) recommended the transition frequency of the P(16) line of the $^{13}\text{C}_2\text{H}_2$, at 194 369 569.4(1) MHz for the practical realization of a meter as a relevant frequency reference in the optical communications spectral region [12]. CIPM recommended the P(16) line of $^{13}\text{C}_2\text{H}_2$ because there have been sufficient studies on this transition. The stability of the acetylene-stabilized laser at the transition is $1.2 \times 10^{-11}/\tau^{1/2}$ [13].

In this paper, we have observed the saturated absorption spectrum and stabilized the frequency of a laser diode into the P(16) line of $^{13}\text{C}_2\text{H}_2$ in order to develop the optical frequency standard in the near infrared region. To obtain a sub-Doppler saturated absorption spectrum using a low-power laser diode, we used external-cavity spectroscopy. The laser stabilized to the saturated absorption spectrum will be used as an optical frequency standard in the 1.5 μm region.

II. EXPERIMENTAL SETUP

To observe the saturated absorption of acetylene molecules, two effects should be considered; the absorption is low and the saturation intensity is high. In the case of the transition $\nu_1+\nu_3$ band of $^{13}\text{C}_2\text{H}_2$, the key parameters for the saturated absorption spectroscopy are the linear absorption coefficient (α), saturation intensity (I_s), pressure broadening, and transit-time broadening. Table 1 shows the values of these parameters.

TABLE 1. Values for the saturated absorption spectroscopy of acetylene molecule.

	Value	Unit or Expect	Ref.
Linear absorption coefficient (α)	3×10^{-3}	$1/(\text{cm Torr})$	[3]
Saturation intensity (I_s)	$15 \times 10^3 (0.1 + 10p)^2$ $p(\text{Torr})$	mW/mm^2	[3]
Pressure broadening	on average $\sim 6 \text{ MHz}/\text{Torr}$	$p = 10 \text{ to } 50 \text{ mTorr}$ $\delta\omega = 60 \text{ kHz to } 300 \text{ kHz}$	[14]
Transit-time broadening	$\delta\omega \cong \sqrt{2 \ln 2} v/w$	at room temp. $\langle v \rangle = 400 \text{ m/s}$, $w = 1 \text{ mm}$ $\delta\omega_t = 500 \text{ kHz}$	[15]

Figure 1 shows the experimental scheme for the external-cavity spectroscopy in the acetylene molecule $^{13}\text{C}_2\text{H}_2$. The diode laser used in this work is a commercially available extended cavity laser diode (ECLD) using the Littman configuration. The single-mode output power is typically 2.0 mW and the free-running laser linewidth is less than 1 MHz. To obtain sufficient power, we used an erbium doped fiber amplifier (EDFA) which amplifies the ECLD's power up to 50 mW. The output beam is directed through a 60 dB isolator and a half-wave plate onto a polarizing beam-splitter, where the half-wave plate orientation controls the power going to the external cavity absorption cell.

The external cavity absorption cell consists of a 20

cm long Brewster-window quartz cell filled with $^{13}\text{C}_2\text{H}_2$ at a pressure of 30 mTorr and a 25 cm long passive plano-spherical resonator with mirror reflectivities of 98.5% and with a spherical mirror curvature of 1 m. The FSR (free spectral range) and the finesse of the resonator are 600 MHz and 200, respectively.

To keep the resonance condition between the laser frequency and the resonator, the Pound-Drever-Hall stabilization technique is adopted [16]. Using an electrooptic modulator (EOM) driven at a frequency 5 MHz, the laser frequency is locked to the resonance of the resonator. After passing through the EOM, the laser beam is coupled into the resonator via a mode-matching lens, with an input coupling efficiency of about 70%.

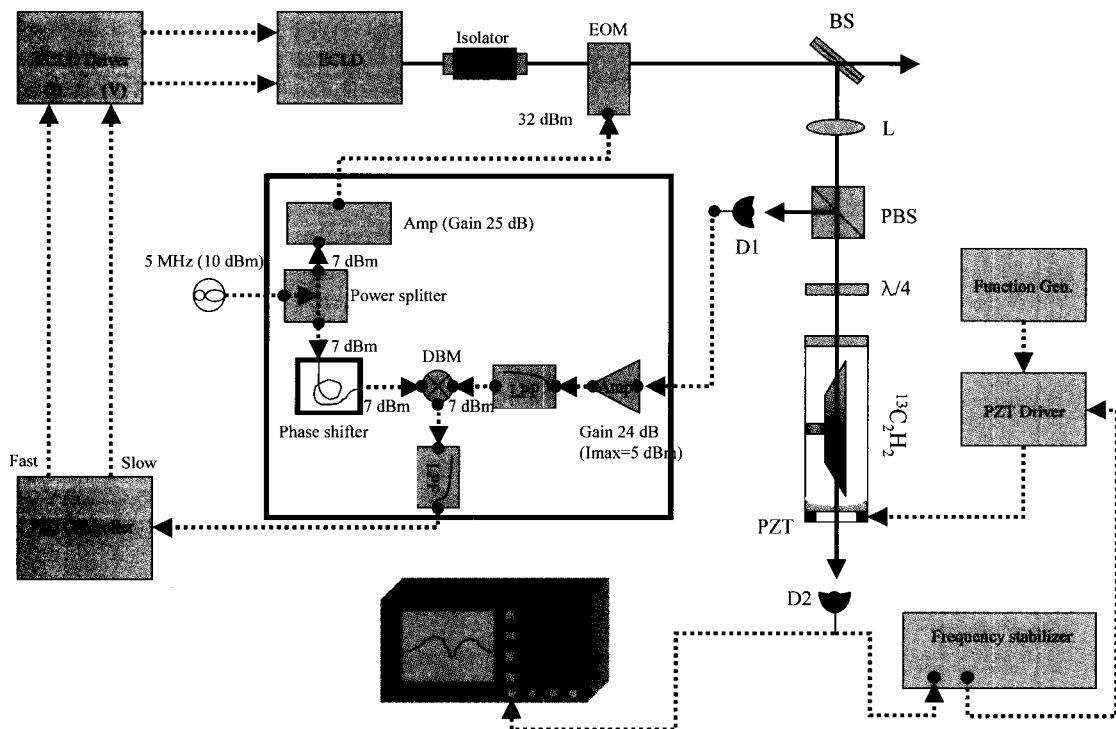


FIG. 1. Experimental setup for saturated absorption spectroscopy using external-cavity technique.

(Amp; RF amplifier, LPF; low pass filter, DBM; double balanced mixer, BS; beam splitter, PBS; polarizing beam splitter, PD; photo diode)

The resonant signal is obtained from the reflected beam from the resonator using a detector (D1). The laser frequency is locked to the resonance of the resonator using an electronic servo system. The output of this servo loop is closed to the laser PZT and the laser current.

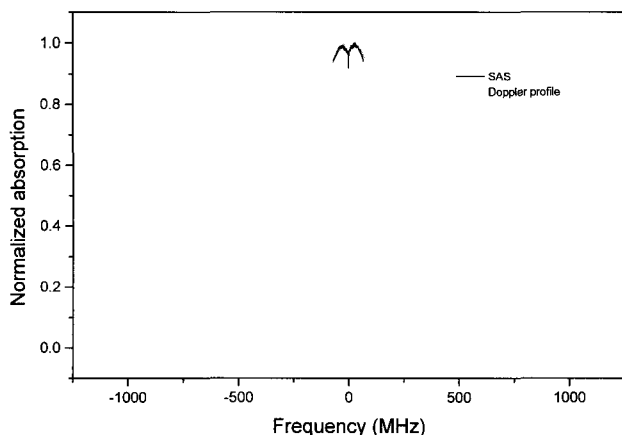
The laser frequency locked to the resonance of the resonator can be scanned by changing the length of the resonator using its PZT. We can observe the saturated absorption signals of the acetylene by detecting the resonator transmission (D2).

To stabilize the laser frequency to the saturated absorption signal, we applied a 500 Hz modulation signal to the resonator PZT and obtained the first derivative of its signal using a lock-in amplifier. The error signal of the lock-in amplifier is fed back into the resonator PZT.

III. RESULTS AND DISCUSSION

A. Saturated absorption spectroscopy of the $^{13}\text{C}_2\text{H}_2$

We studied the saturated absorption spectroscopy of the P(16) line of the $^{13}\text{C}_2\text{H}_2$, which was recently recommended by CCL for the realization of a meter in the 1.5 μm region. Figure 2 (a) shows the linear absorption spectrum of the P(16) line of $^{13}\text{C}_2\text{H}_2$. For an acetylene molecule at low-pressure, the effect of Doppler is more dominant than the collision broadening because this spectrum has a Gaussian profile. The linewidth of the linear absorption is about 500 MHz at the room temperature and the absorption is about 20%. The black curve in the peak of the linear absorption represents



(a) Linear absorption spectrum of the P(16) transition of $^{13}\text{C}_2\text{H}_2$ molecule (gray: linear absorption, black: saturated absorption)

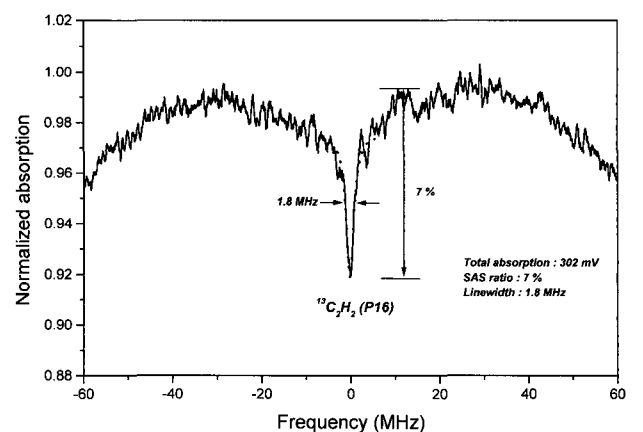
the saturated absorption spectrum.

The saturated absorption spectrum is shown in Fig. 2 (b). This spectrum is obtained using the external-cavity technique. The laser power and the diameter incident on the resonator are 5 mW and 2 mm, respectively. In this spectrum, the relative contrast of the saturated absorption signal with respect to the linear absorption is measured to be approximately 7%. The linewidth of the saturated absorption is 1.8 MHz. The spectral broadening can be considered to arise from the linewidth of the laser (~ 1 MHz), the resonator frequency jitter, and the power broadening. Our results agree with other results obtained under similar conditions [6-8]. To improve the characteristics of the saturated absorption spectrum, we need to reduce the linewidth using a high-Q resonator and improve the external environmental conditions such as vibration and electrical noise.

B. Frequency stabilization to the saturated absorption spectrum

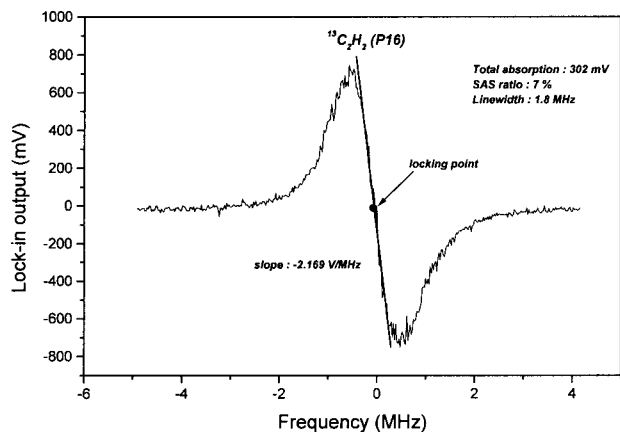
When using the external-cavity technique, two separate servo loops should be used in the stabilization scheme in order to stabilize the laser frequency to the saturated absorption signal. The first servo loop uses a double-balanced mixer and a loop filter to stabilize the laser frequency to the resonant mode of the resonator. The second servo loop uses a lock-in amplifier with a 500 Hz modulation signal to stabilize the resonant mode to the saturated absorption signal.

The first derivative signal of the P(16) saturated absorption spectrum by the lock-in amplifier is shown in Fig. 3 (a). The dispersive error signal is fed back into the resonator PZT, and the laser frequency is then

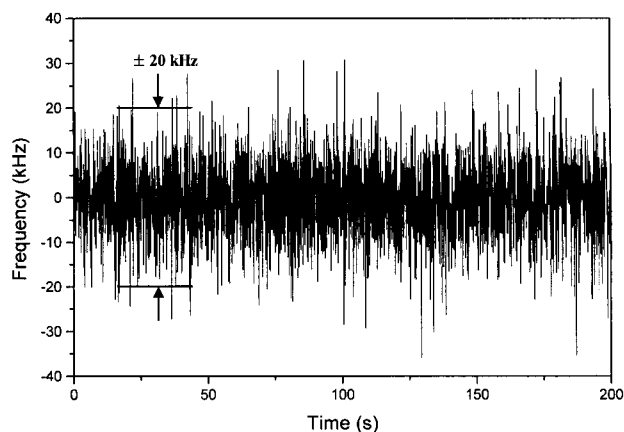


(b) Saturated absorption spectrum of the P(16) transition of $^{13}\text{C}_2\text{H}_2$ molecule

FIG. 2



(a) First harmonic signal of the lock-in amplifier



(b) Frequency fluctuation of the stabilized laser for a sampling time of 100 ms

FIG. 3

stabilized to the peak of the saturated absorption signal.

In order to estimate the laser frequency stabilization, we measured the error signal of the lock-in amplifier of the second servo loop with a sampling time of 0.1 s. The voltages of the error signal can be converted to the laser frequency by the slope of the first derivative signal (-2.169 V/MHz). The laser frequency fluctuation is ± 20 kHz for a sampling time of 100 ms, as shown in Fig. 3 (b).

IV. CONCLUSIONS

We observed the saturated absorption spectrum using the external-cavity technique and stabilized the frequency of a laser diode into the P(16) line of $^{13}\text{C}_2\text{H}_2$. To obtain the saturated absorption spectrum, the resonance condition between the laser frequency and the resonator was maintained by the Pound-Drever-Hall technique. The measured linewidth and contrast of the saturated absorption spectrum were 1.8 MHz and 7%, respectively. When the laser frequency was stabilized to the peak of the saturated absorption signal, the frequency fluctuation of the stabilized LD was about ± 20 kHz for a sampling of time 100 ms.

Development of the optical frequency standard in 1.5 μm region using the acetylene molecule is in progress. Based on our results, we will find improvements toward attaining the optimal conditions. The optical frequency and the uncertainty of the stabilized laser will be measured in order to use it as the optical frequency standard for optical communication.

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