OPTICAL FREQUENCY STANDARD AT 194 369 569.4(5) MHz BY SOLID-STATE LASER LOCKED AGAINST P(16) LINE OF $^{13}C_2H_2$

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Abstract — The recently developed fiber-pumped Er-Yb:glass laser was used to perform saturation spectroscopy and frequency locking with respect to P(16) acetylene line. With the available 10 mW laser power, we used a Fabry-Perot build-up cavity to achieve a 1.2 MHz wide saturation dip with 7 % line contrast. A novel optical frequency standard, based on this solid-state laser locked to the saturated absorption of $^{13}C_2H_2$ P(16) line was achieved. A peak-to-peak frequency stability of $\pm$20 kHz was measured in 500 Hz bandwidth whereas the Allan deviation, calculated from the error signal, gives a relative frequency stability $\sigma_y(\tau)<10^{-12}$ for τ>70 s.

Keywords: stabilized laser, optical frequency standard, 1.5 μm, acetylene.

1. INTRODUCTION

Optical frequency standards in the Near Infrared Region of the electromagnetic spectrum are becoming more and more important for different scientific and practical applications. Stable and accurate frequency standards are already well established at λ=1.064 μm, they are intensively pursued at λ=1.5 μm and they will be a next challenge at around 2 μm wavelength. For optical fiber communication systems, Refs. 1, 2, optical fiber sensors, Ref. 3, high-resolution spectroscopy and metrology applications, a frequency-stabilized reference laser source in the 1.5 μm spectral region (ν~200 THz) is of significantly great interest. In this regard, the rovibrational line P(16) at λ~1.5344 μm of the acetylene molecule, namely in its isotopic version $^{13}C_2H_2$, was very recently recommended by the *Comité Consultatif pour la Longueur* of the CIPM for the practical realization of the meter, Ref. 4, with a proposed frequency value of 194 369 569.4(1) MHz.

In recent years many groups have worked toward the development of an optical frequency standard in the 1.5 μm region, Refs 5, 6, based on both atomic, Refs 7-10, and molecular, Refs 11-14, references. In this paper we will report recent results achieved in our group using a fiber-pumped solid-state bulk erbium microlaser and saturated absorptions of the $^{13}C_2H_2$ molecule.

2. THE ERBIUM MICROLASER

A massive, compact, and diode-pumped Er-Yb:glass laser resonator was developed in our laboratories, Ref. 15. The design was focused on the mechanical stability, reliability, and wide wavelength tunability of this single frequency laser oscillator. Low frequency noise operation was observed for the free-running oscillator over relatively long observation periods. The active medium, used as the plane mirror of the optical resonator, is end pumped by a fiber coupled 1 W diode laser at 980 nm. The resonator was optimized for maximum overlapping of the pump beam and fundamental TEM_{00} laser mode. A 50 μm thick BK7 etalon coated on both surfaces allows for coarse wavelength tunability while an annular piezoelectric transducer, glued to the spherical output coupler, finely tunes the oscillation frequency. An intracavity Brewster plate selects linear polarization with a remarkably good extinction ratio (>30 dB). Typical single-frequency output powers of ~10 mW have been achieved with a continuous tunability range from 1532 nm to 1549 nm. Recent improvements on this oscillator allowed enhancing of the power level to ~20 mW, with unchanged noise immunity.

A schematic drawing of the fiber-pumped Er-Yb:galss laser is shown in Fig. 1.

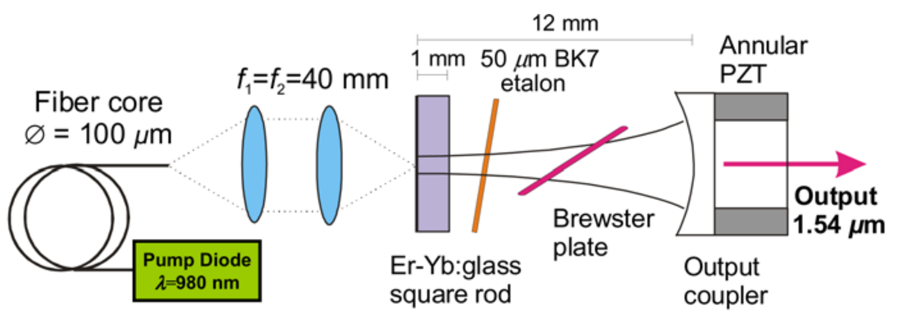

Figure 1 Schematic diagram of the Er-Yb:glass laser: pumping scheme and laser cavity.

3. $^{13}C_2H_2$ REFERENCE AND SPECTROSCOPY

Isotopic acetylene ($^{13}C_2H_2$) was used as a molecular reference since this molecule provides for a broad rovibrational absorption band in the wavelength region around 1.54 μm. Some 30 strong an well resolved absorption lines are available from this molecule at wavelengths from 1534 nm to 1552 nm. In addition these lines are not complicated by a hyperfine structure and the molecule itself is free of permanent electric dipole.

The gas sample we used, at 4 Pa pressure, was contained in a sealed Brewster-windows 200 mm quartz cell, placed within a plano-spherical 300 mm long optical resonator. The reflectivity of the build-up cavity mirrors was equal to 98.5 % power reflectivity. The observed Finesse of the Fabry-Perot structure containing the gas cell was ~120 on the line resonance. The laser output beam was passed through a 60 dB optical isolator, an electrooptical modulator for a Pound-Drever frequency locking to the build-up cavity, and then through the frequency reference (see Fig. 2). By supplying the laser frequency actuator (a piezoelectric transducer glued to the output mirror) with a voltage ramp, it was possible to scan the laser frequency across the molecular absorption (~500 MHz wide from Doppler broadening). Doppler-free absorptions were observed for all the lines from P(10) to P(16) and in all cases we could observe a well resolved saturation dip at the line center. In particular, Fig. 3 shows the absorption dip recorded in the line center of transition P(16) at a frequency of 194 369 569.4(1) MHz. The full width of this saturated line dip is 1 MHz with a relative contrast of 7 % to the corresponding Doppler absorption.

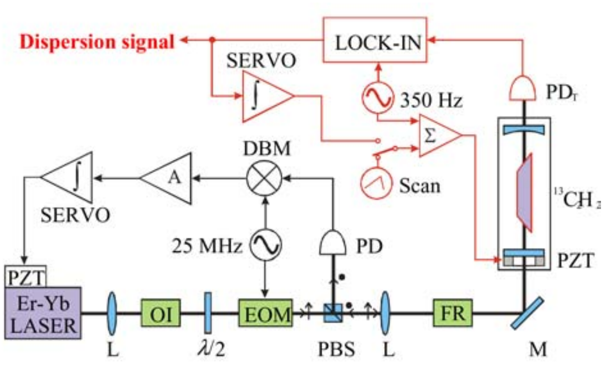

Figure 2 Experimental set up for saturation spectroscopy and frequency locking to $^{13}C_2H_2$. L: lens; OI: optical isolator; PBS polarizing beam splitter; FR: Faraday rotator; PD: photo detector; A: amplifier; PZT: piezoelectric transducer.

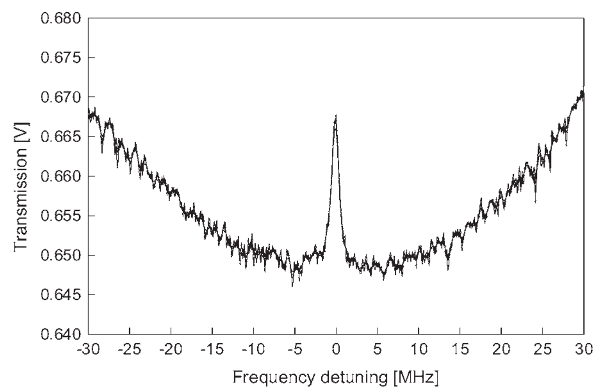

Figure 3 Saturated absorption line at the bottom of the transmission spectrum of the P(16) Doppler transition.

4. FREQUENCY LOCKING AND RESULTS

In order to lock the laser to the external resonator, the beam was phase modulated, at a modulation frequency of 25 MHz, outside of the cavity using an electro-optical modulator (EOM, New Focus mod. 4004). The phase-modulated beam was coupled into the enhancement resonator trough suitable mode-matching optics. The measured coupling efficiency was >70 %. The reflected beam from the external Fabry-Perot was photo-detected, demodulated in the first harmonic of the modulating signal and eventually filtered to obtain the odd error signal for the first frequency control loop. This error signal was fed back to the frequency actuator, locking in this way the laser frequency to a fundamental (TEM_{00}) resonance of the external resonator. Limited by the first mechanical resonance of the piezoelectric transducer used as the laser frequency actuator, the bandwidth of this feedback loop was measured to be approximately 1.5 kHz. The frequency of the whole optical system was then dithered applying a 400 Hz modulation signal to another piezoelectric transducer glued on one mirror of the external Fabry-Perot resonator. This second modulation frequency was chosen to be well below the cutoff frequency of the first feedback loop to avoid phase delays that could give rise to oscillations. First-harmonic coherent detection of the transmitted beam (PD_T) with a lock in amplifier (EG&G, mod. 7265) led to the saturated dispersion signal shown in Fig. 4. This error signal was fed back, through a high order loop filter, to the laser PZT in order to lock the laser frequency to the saturated line. The measured loop bandwidth of this second control loop was ~150 Hz.

The high level of laser output power and its intrinsic narrow linewidth, combined with the good coupling efficiency to the external build-up cavity (with relatively high resonator finesse), allowed reaching interesting results: the observed saturation dip shows a relative line contrast of 7.5 % with respect to the Doppler line, and a significant slope of the error signal, about 2 V/MHz, was obtained in this way with a signal to noise ratio of 40 dB in a 3 Hz bandwidth (Fig. 4).

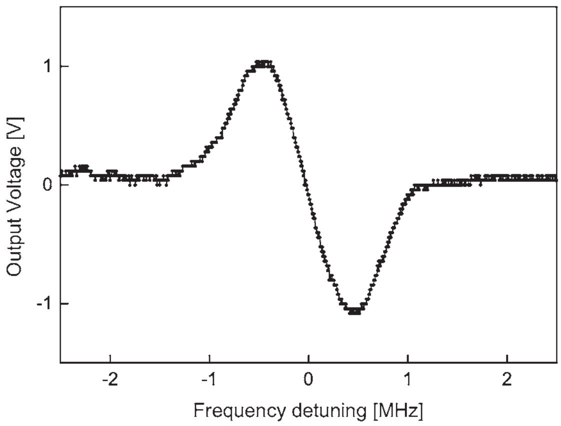

Figure 4 First derivative signal of P(16) line in a 3 Hz bandwidth (at the lock-in amplifier).

Since only one frequency stabilized Er-laser/$^{13}C_2H_2$ system was developed, we inferred the achieved frequency stability from the error signal of the control loop used to lock the laser frequency to the molecular transition. This signal, at the lock-in amplifier output, was recorded with a sampling frequency of 500 Hz and its observation over 500 s is shown in Fig. 5. To calculate frequency deviations from recorded voltage values, the error signal was divided by the discriminator slope of 2 V/MHz. The peak-to-peak fluctuations in Fig. 5 show a maximum frequency deviation of approximately ±40 kHz whereas the corresponding rms fluctuation is 9.7 kHz. This last value is further reduced to 1.7 kHz ($\Delta\nu/\nu$=8.7×10^{-12}) with 1 s integration time. The calculated Allan deviation, for the laser frequency fluctuations of Fig. 5, reaches a floor level <10^{-12} for an integration time >70 s.

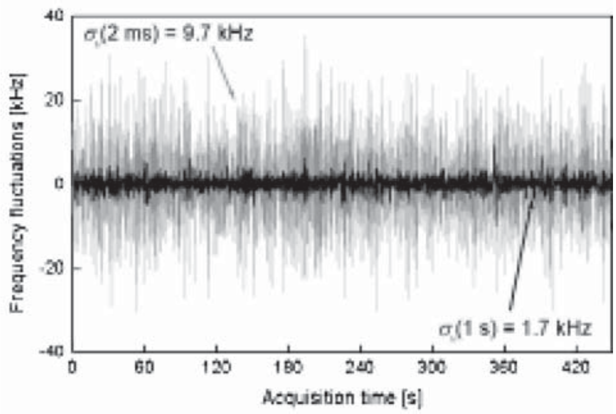

Figure 5 Residual frequency fluctuations when the laser is locked to the P(16) saturated line.

With the same experimental setup, the erbium laser was also locked to other saturated absorptions of $^{13}C_2H_2$. Namely, lines from P(10) to P(16), could be easily reached and locked to with similar spectroscopic and frequency stability results to the ones obtained for line P(16).

In the case of line P(16), since its transition frequency is known with an accuracy of 100 kHz and the full width of the saturated line is ~1 MHz, we can infer a ±500 kHz accuracy level for our Er-laser/$^{13}C_2H_2$ optical frequency standard.

5. CONCLUSIONS

We locked the 1.5 μm Er-Yb laser to different saturated absorption lines of the P branch of the $^{13}C_2H_2$ ($\nu_1+\nu_3$) transition just in coincidence with the third optical fiber transmission window. Through a suitable design of the laser resonator and a high order feedback filter we obtained frequency stability in the range of 10^{-11} and an estimated accuracy in the range of 10^{-9}. To better quantify this last important parameter a second frequency-stabilized laser system and beat frequency measurements will be required.

REFERENCES

[1] ITU-T Recommendation G.962, “Optical interfaces for multichannel systems with optical amplifiers”, 1998.

[2] P. Hansell and H. Leeson, "Absolute frequency standards for optical communications", *NPL—Requirements Survey* PRO-AFS-FR-2, 1992.

[3] A. Arie, B. Lissak, and M. Tur, "Static fiber-Bragg grating strain sensing using frequency-locked lasers", *J. Lightwave Technol.*, vol. 17, pp. 1849-1855, 1999.

[4] CCL Meeting, Paris, Sept. 2001.

[5] D. J. E. Knight, "Laser frequency standards and frequency measurement for the optical fibre band", *Proc. of 2nd European Frequency and time Forum*, Neuchatel (CH), pp. 23-33.

[6] K. Nakagawa, M. de Labachelerie, Y. Awaji, and M. Kourogi, "Accurate optical frequency atlas of the 1.5-μm bands of acetylene", *J. Opt. Soc. Am. B*, vol. 13, pp. 2708-2714, 1996.

[7] Y. C. Chung and C. B. Roxlo, "Frequency-locking of 1.5 μm DFB laser to an atomic krypton line using optogalvanic effect." *IEE Electron. Lett.*, vol. 24, pp. 1048-1049, 1988.

[8] M. Ohtsu and E. Ikegami, "Frequency stabilization of 1.5 μm DFB laser using internal second harmonic generation and atomic ^{87}Rb line", *IEE Electron. Lett.*, vol. 25, pp. 22-23, 1989.

[9] A. Bruner, A. Arie, M. A. Arbore and M. M. Fejer, "Frequency stabilization of a diode laser at 1540 nm by locking to sub-Doppler lines of potassium at 770 nm", *Appl. Opt.*, vol. 37, pp. 1049-1052, 1998.

[10] C. Svelto, F. Ferrario, A. Arie, M. A. Arbore, and M. M. Fejer, "Frequency stabilization of a novel 1.5 μm Er-Yb bulk laser to a ^{39}K sub-Doppler line at 770.1 nm", *IEEE J. Quantum Electron.*, vol. 37, pp. 505-510, 2001.

[11] S. Sudo, Y. Sakai, H. Yasaka, and T. Ikegami, "Frequency Stabilization of 1.55 μm DFB Laser Diode Using Vibrational-Rotational Absorption of $^{13}C_2H_2$ Molecules", *IEEE Photon. Technol. Lett.*, vol. 1, pp. 392-394, 1989.

[12] F. Bertinetto, P. Gambini, R. Lano, and M. Puleo, "Stabilization of the Emission Frequency of 1.54 μm DFB Laser Diodes to Hydrogen Iodide", *IEEE Photon. Technol. Lett.*, vol. 4, pp. 472-474, 1993.

[13] C. Svelto, E. Bava, S. Taccheo, and P. Laporta, "Pound-Drever frequency stabilised Yb-Er:glass laser against C_2H_2 molecule at 1.534097 μm", *IEE Electron. Lett.*, vol. 34, pp. 461-462, 1998.

[14] 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 acetylene overtone band transition", *IEEE Trans. Instrum. Meas.*, vol. 48, pp. 563-566, 1999.

[15] C. Svelto, G. Galzerano, F. Ferrario, and E. Bava, "Novel fiber-pumped quasi-monolithic Er-Yb:glass laser with single-frequency output power of 60 mW at 1.534 μm", Proc. of 14th European Frequency and time Forum, Turin (IT), pp. 528-531, 2001.