FREQUENCY STABILIZED Er-Yb LASER ON $^{13}C_2H_2$ SATURATED ABSORPTIONS AT AROUND 1.54 μm

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ABSTRACT

A novel and compact diode-pumped Er-Yb:glass laser, with single-frequency output power up to 20 mW in a wavelength range from 1531 nm to 1547 nm, was frequency stabilized with respect to sub-Doppler rovibrational transitions of $^{13}C_2H_2$. The laser frequency was locked to these molecular lines by means of the non-linear wavelength-modulation spectroscopy technique. The relative frequency stability of the realized Er-Yb:glass-laser-($^{13}C_2H_2$) optical standard is mainly dominated by a white frequency-noise contribution which sets an Allan deviation at a level of $\sigma_y=7.5\times10^{-12}\tau^{-1/2}$ for integration times in the range of 0.01 s<τ<100 s.

INTRODUCTION

Optical frequency standards in the Near Infrared Region of the electromagnetic spectrum are becoming more and more important for several 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 [1, 2] optical fiber sensors [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 [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 [5, 6] based on both atomic [7-10], and molecular [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.

ER-YB:GLASS LASER

The main characteristics of the developed diode-pumped Er-Yb:glass microlaser are its cavity design, with a very compact and noise insensitive massive resonator, and the use of longitudinal fiber-coupled diode pumping at the 980 nm. As compared to previous versions of this laser source, a substantial reduction of the free-running laser frequency noise, mainly due to mechanical vibrations has been achieved. The use of a phosphate glass host for the active Er^{3+} ions allows for very broad and continuous wavelength tunability in the 1.54 µm spectral region: in particular, this oscillator is continuously tunable, in single-frequency operation, from 1531 nm to 1547 nm. The output beam is in a diffraction-limited TEM_{00} mode and in a linear polarization state with 30 dB extinction ratio. During the frequency stabilization experiments, the laser is operated at around 1.54 µm wavelength with 14 mW output power and at room temperature conditions. In particular, single longitudinal mode selection is obtained by inserting within the laser cavity a 50 µm thick BK-7 etalon, coated for 10 % reflectivity at the laser wavelength. The coarse spectral tuning of the output wavelength is achieved by tilting this intracavity etalon and exploiting the whole etalon free spectral range of 16 nm. Typical oscillation linewidth is below 50 kHz for an observation time of 1 ms. An annular piezoelectric transducer (PZT), glued to the output mirror, allows for fine tuning of the cavity length and thus of the laser frequency. The mode-hop-free frequency tuning range is approx. 10 GHz with a voltage-to-frequency tuning coefficient of 290 MHz/V. This frequency span is wide enough to carry out high-resolution laser spectroscopy of different atomic/molecular transitions falling in the laser spectral region.

ABSOLUTE FREQUENCY SATBILIZATION OF THE ER-YB:GLASS OSCILLATOR

Acetylene ($\nu_1 + \nu_3$) rovibrational absorption bands at 1.54 µm wavelength provide for very interesting absolute frequency references in this near-infrared spectral region. In our experiment, in order to obtain a saturated absorption signal, a 20 cm long Brewster-window quartz cell filled with $^{13}C_2H_2$ at a pressure of 4 Pa is placed inside a Fabry-Perot build-up cavity. To keep the resonance condition between the laser frequency and the Fabry-Perot cavity, a standard Pound-Drever-Hall stabilization system was adopted closing the stabilization loop to the laser PZT. With the laser frequency locked to the cavity resonance, by scanning the length of the passive resonator using its PZT, it was possible to observe the saturated absorption profile of different $^{13}C_2H_2$ rovibrational lines by means of the cavity transmission signal. When observing the P(14) saturated line, a Lamb-dip of relative contrast of 7.5 % with respect to the linear absorption is measured, with a full width of 1.2 MHz. The first derivative signal of the saturated absorption is obtained by means of wavelength modulation of the laser radiation and by sending to a lock-in amplifier the output voltage from the photodiode detecting the Fabry-Perot transmission. The obtained first derivative for the P(14) saturated line shows a slope of 2 µV/Hz at the resonance center and a SNR of 40 dB in 2 Hz measurement bandwidth. Using this frequency discriminating signal a second control loop is used for the stabilization of the Fabry-Perot resonance (to which the laser frequency is locked) against the saturated feature. When both control loops are closed, the residual error signal at the lock-in amplifier output shows peak-to-peak frequency fluctuations of ±40 kHz for observation times in the order of tens of minutes when recorded with a a sampling frequency of 500 Hz (see Figure 1).

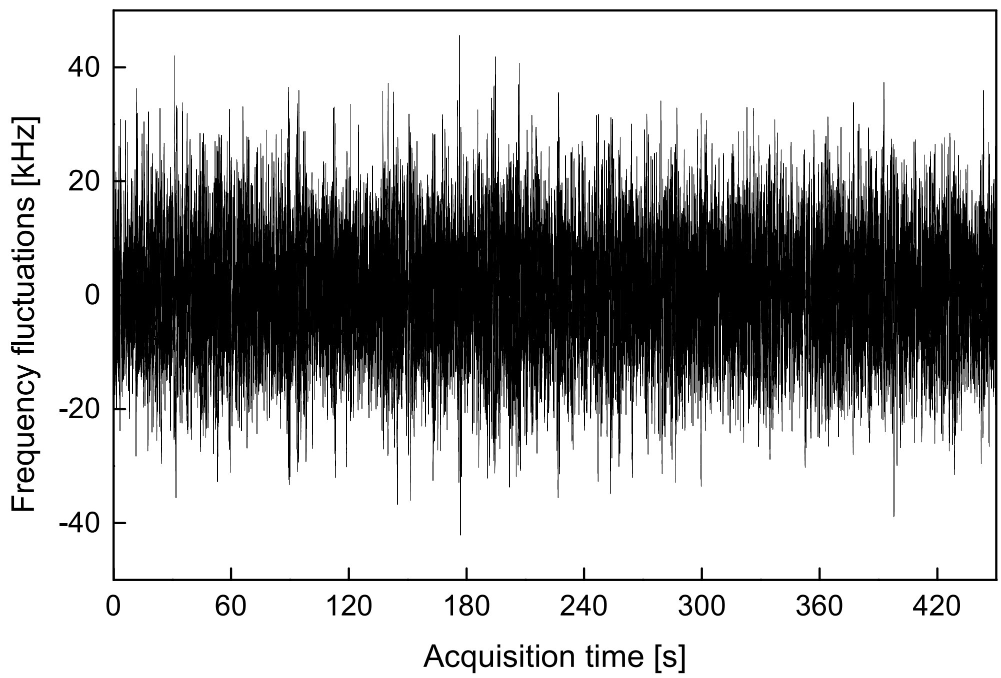

Fig. 1. Residual laser frequency fluctuations when the oscillator is locked to the P(14) $^{13}C_2H_2$ saturated line.

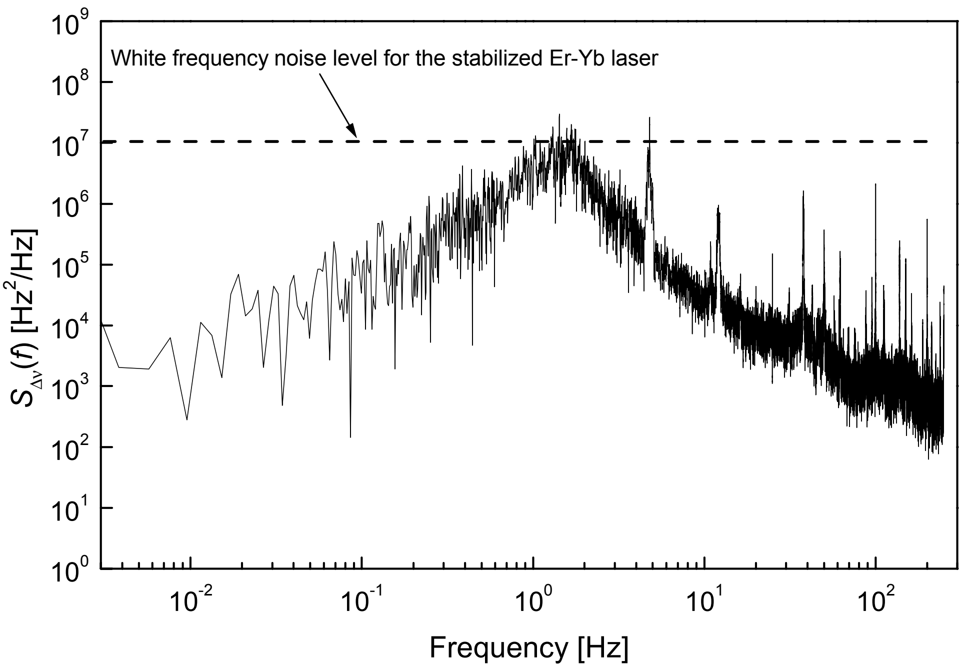

Fig. 2. Power spectral density of the error signal.

From the time-recording of Fig. 1 the numerical FFT spectrum of the frequency fluctuations was calculated (see Figure 2). The power spectral density of the error signal shows a roll-off of –20 dB/dec for Fourier frequencies higher than 2 Hz due to the output bandwidth of the lock-in amplifier (the lock-in integration time was set to 100 ms), as it is shown in the diagram of Fig. 2. On the other side, for frequencies lower than 2 Hz the power spectral density is well characterized by a continuous slope of +20 dB/dec, which is due to the high stabilization loop gain. Taking into account the servo-loop transfer function, the power spectral density of the frequency fluctuations of the stabilized Er-Yb:glass laser is characterized by a white frequency noise contribution at a level of 10^7 Hz^2/Hz (dashed line in Fig. 2). This level of frequency noise corresponds to a relative Allan deviation lower than 10^{-11} for integration times of 1 s.
Laser frequency stabilization against the line P(16), recently recommended by the CIPM as an optical frequency standard in this spectral region, was also achieved. The reached frequency stability for line P(16) was only a factor square root of two worse than the one obtained using P(14) line, thus remaining at the 10^{-11} level. To assess the accuracy of the developed frequency standard, a second identical system needs to used in order to perform direct beat note measurements. However, due to the modest pressure shift in our experimental condition and from the 1.2 MHz width of the saturated line, we can infer a sub-megahertz accuracy for the stabilized laser.

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.

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