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STABILIZATION OF A 2.1 μm DIODE-PUMPED Tm-Ho:YAG LASER AGAINST LINEAR TRANSITIONS OF CO_2

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Abstract - **Absolute frequency stabilization of 2.1 μm diode-pumped Tm-Ho:YAG lasers at 2.1 μm is reported. Different rotovibrational absorption lines of CO_2 were used as absolute frequency references. The frequency control of a custom made, single-frequency and tunable Tm-Ho:YAG lasers was achieved by means of two linear spectroscopy methods: the fringe-side locking method and the wavelength modulation technique. Comparison between the experimental results obtained using these two methods is also reported. With both locking methods a significant improvement of the laser frequency stability was obtained. In particular a minimum value of frequency stability of 20 kHz at 1 s integration time was achieved using the wavelength modulation method, whereas for the fringe-side technique a minimum stability of 100 kHz was obtained for an integration time of 10 ms. The achieved stability levels are more than one order of magnitude better than typical Doppler- Lidar system requirements.**

Keywords - **Frequency noise measurement, molecular spectroscopy, frequency stabilization, solid-state laser, DIAL and LIDAR applications.**

I. INTRODUCTION

A variety of eye-safe diode-pumped solid-state lasers operating around the 2-μm wavelength are nowadays under development for applications to remote sensing and medicine. In particular, the development of frequency-stabilized 2 μm laser sources is of great interest for coherent Doppler velocimetry Lidar and high-sensitivity Differential Absorption Lidar (for carbon dioxide and water vapor measurements) systems and for other fundamental applications, such as high resolution spectroscopy, and optical metrology [1 4].

Very good spectral properties of the laser source are required for all these applications in order to achieve high system performance. Diode-pumped Tm-Ho:YAG lasers oscillating at around 2090 nm are very promising candidates to this aim, due to their intrinsic stability, excellent beam quality, and wide wavelength tunability (Ref. 5) in the 2080 nm–2100 nm spectral region, where several transitions of carbon dioxide and water vapor are available.

In this work we report on the absolute frequency stabilization of a single-frequency diode-pumped Tm-Ho:YAG laser to absorption lines of CO_2. Two different frequency locking technique was used: the fringe-side locking method and the wavelength modulation technique.

II. DIODE-PUMPED TM-HO:YAG LASER

The laser resonator, ~50 mm long, has a plano-spherical configuration, with an output coupler of 55 mm radius of curvature and 1 % transmission at the laser wavelength. The active medium is a 3 mm thick Tm-Ho:YAG rod, doped with 6 % Tm and 0.36% Ho concentrations. A dichroic coating (reflectivity > 99.9 % at 2090 nm and transmission > 93 % at 785 nm) on the external face acts as the total reflector, whereas the internal face is antireflection coated at the laser wavelength. The active rod is longitudinally pumped by the 3 W broad area GaAlAs laser diode with a collimating microlens for the fast axis. A simple spherical lens with 50 mm focal length is used to focus the pump beam in the active medium as a 1:1 image of the beam waist at the output of the diode microlens, and the transverse profile of the pump beam inside the rod has approximately constant dimensions of 30 μm × 120 μm. Single-frequency operation and wavelength tuning are achieved by two intracavity uncoated BK7 etalons, 100 μm and 300 μm thick, respectively. An annular piezoelectric transducer (PZT) glued to the output mirror allows for fine electrically driven frequency control, within the cavity free spectral range, of ~2.9 GHz. We measured a quasi-continuous tuning range of the emission wavelength from 2087 nm to 2099 nm. In single-mode operation the threshold power is ~300 mW and the maximum output power is 42 mW for emission wavelength of 2097 nm.

III. SPECTROSCOPY OF CO_2 AROUND 2.1 μm

High-resolution spectroscopy of CO_2 at 2.1 μm was performed by using a 77-passes cell (path length 29.26 m), filled with CO_2, to increase the peak absorption. The pressure was set to ~11 kPa, corresponding to the best slope for the transmission curve. The laser frequency was swept over a free-spectral-range by applying a ramp voltage to the PZT, and two photodiodes, connected in a differential scheme, were used to cancel common mode intensity fluctuations of the laser induced by the PZT displacement. Several absorption lines, namely from P(21) up to P(36),

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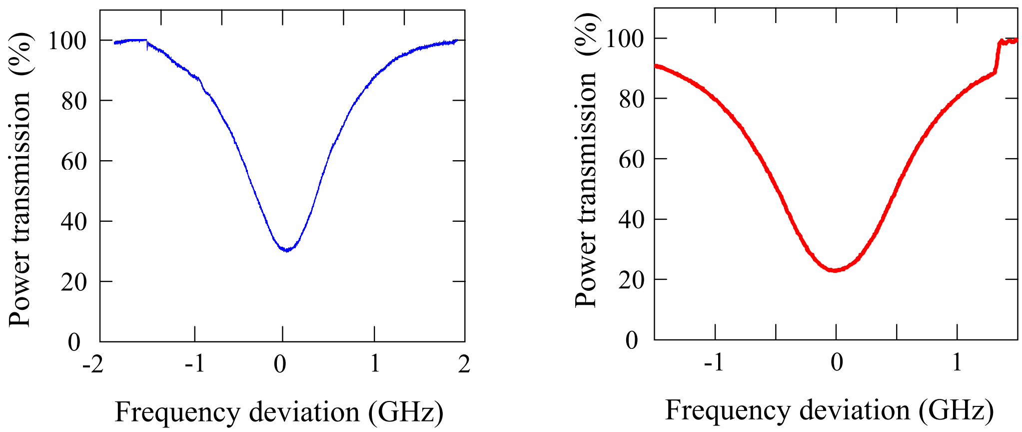

Figure 1. Transmission spectrum of the P(32) a) and P(22) b) lines located at 2091.692 nm and 2087.844 nm, respectively.

were measured, falling in the 2087-2095 nm spectral range. Figures 1a and 1b show a typical recording of the transmission spectrum of the P(32) and P(22) lines located at 2091.692 nm and 2087.844 nm, respectively. The measured full width at half maximum (FWHM) are 1.1 GHz and 1.28 GHz, respectively and the peak absorptions are 70% and 77%, respectively.

IV. Laser Frequency Stabilization

The Tm-Ho:YAG laser frequency was locked to CO_2 transitions by means of the fringe side locking technique (see Ref. 6), *i.e.* by using one side of the transmission curve as a frequency discriminator, or the frequency modulation method. Two Tm-Ho:YAG lasers were simultaneously locked to the same absorption line in order to evaluate the frequency stability level by beat note measurements. The experimental setup used for frequency locking is shown in Fig. 2.

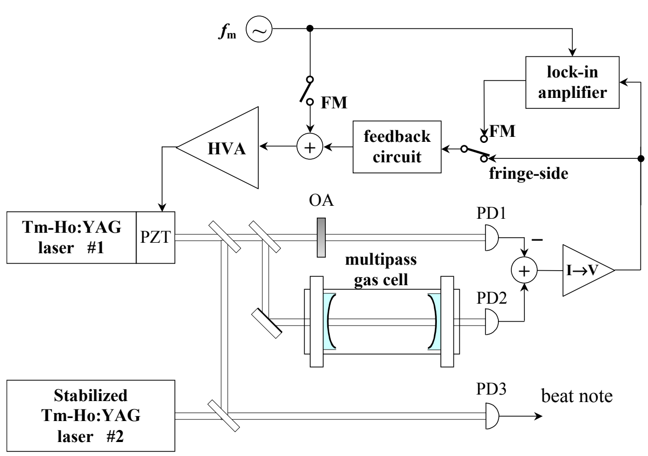

Figure 2. Experimental setup for the absolute frequency stabilization of the Tm-Ho:YAG lasers. The switches shown in the figure select the locking techniques. PD: photodiode; OA: variable optical attenuator; HVA: high-voltage amplifier; I→V: transimpedance amplifier.

In the fringe-side method the operation wavelength was adjusted in proximity of the maximum slope of the absorption line, and then the optical power impinging on photodiodes PD1 and PD2 was equalized. The difference between the two photocurrents was sent to a low-noise transimpedance amplifier, whose output voltage is therefore proportional to the laser frequency deviation from its initial value, at least within small frequency deviations. This output voltage constitutes the error signal and was used both to evaluate the laser frequency noise and to feed the laser frequency actuator through a suitable control circuit. The slope of the frequency discriminator signal was ~0.8 GHz^{-1} (for all the observed CO_2 lines). The feedback circuit ensures high loop gain at low Fourier frequencies and loop stability maintaining the 0 dB crossing point at a frequency (~1 kHz) sufficiently lower than the first mechanical resonance of the PZT-mirror assembly, which is located at ~3 kHz.

The beat note between the two independently stabilized laser was monitored by a fast photodetector (PD3 in Fig. 2), connected to a frequency-to-voltage converter. A recording over 1600 s of the beat frequency fluctuations, measured with both lasers locked to the P(32) line, is shown in Fig. 3. The mean value of the beat note was set to 12 MHz by fine adjustment of photocurrent balance for one of the two stabilized sources. The rms value of frequency fluctuations is 579 kHz, with an acquisition bandwidth of 20 Hz. The beat note was then recorded over 60 s, for comparison, with the two lasers in free running operation: the frequency fluctuations (rms) are 17 MHz in this case. To obtain a more accurate measurement of the achieved frequency stability level, we calculated the Power Spectral Density (PSD) of the beat frequency fluctuations by Discrete Fourier Transform of temporal data, collected on different time scale on a digital oscilloscope, both for the locked and the unlocked condition. An example of the PSD calculated from beat note measurements, with the lasers locked to the P(22) transition of CO_2, is shown in Fig. 4; the dotted curve correspond to the free running operation, with both lasers tuned near 2087.8 nm. The stabilization loop has an effective bandwidth of ~0.6 kHz.

When the FM method was implemented, the laser frequency was modulated by means of a sinusoidal voltage applied to the laser PZT. Modulation frequencies of ~10 kHz were used with frequency modulation depths of about 10 MHz (peak to peak value). A differential detection scheme similar to that previously discussed was used to compensate for laser amplitude fluctuations and in particular to cancel the residual amplitude modulation contribution induced by the frequency modulation. The output signal from the low-noise transimpedance amplifier was sent to a lockin amplifier for synchronous detection. A first harmonic demodulation was adopted in order to retrieve the first derivative of the absorption (dispersion-like signal). The output voltage from the lockin amplifier constitutes the error signal used for the stabilization of the laser frequency. Figure 5 shows the dispersion-like signal corresponding to the P(32) CO_2 line; the slope of the frequency discriminator signal was ~3.3 V/GHz. Also in this experiment the control loop bandwidth is of the order of 1 kHz, essentially limited by the mechanical PZT resonances.

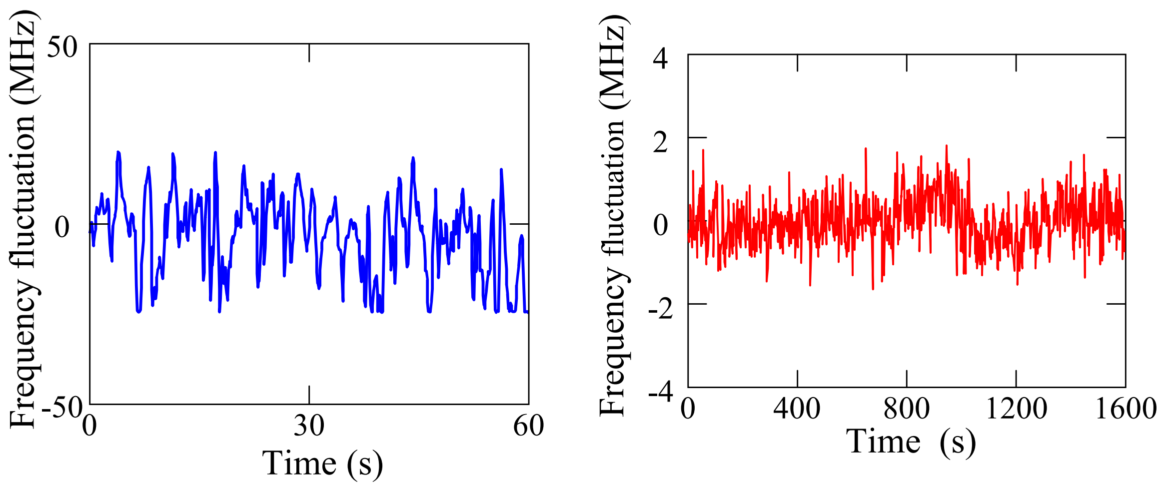

Figure 3. Fluctuations of the beat frequency between the two lasers, independently locked to the P(22) absorption line of at 2087.844 nm.

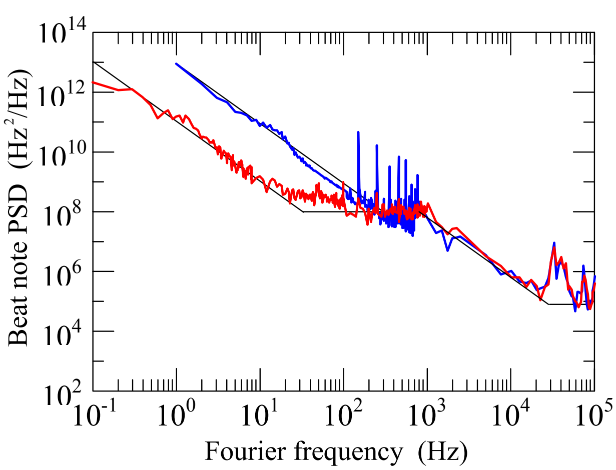

Figure 4. Power Spectral Density of the beat frequency fluctuations with both lasers locked to the P(22) line at 2087.844 nm (solid lines) and in free-running operation (dotted line).

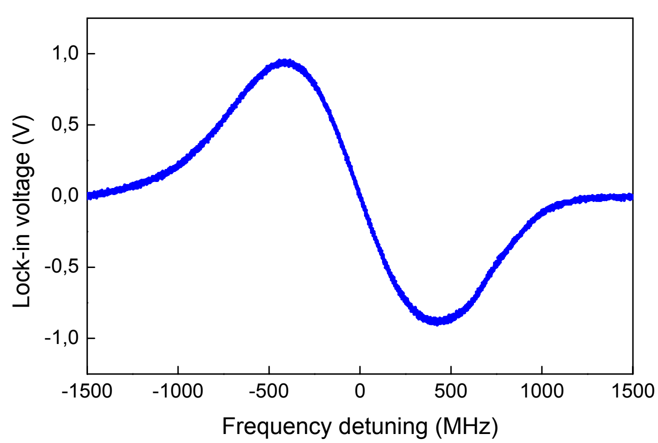

Figure 5. First derivative signal of the P(32) line recovered at the lock-in output (modulation frequency 10 kHz and modulation deviation 10 MHz).

The frequency stability of the two lasers was evaluated by measuring the Allan variance [11], $\sigma_y^2(\tau)$, as a function of the integration time, τ, of the beat note between the two Tm-Ho:YAG lasers. When the lasers were in the free running conditions (filled circles in Fig. 6), the experimental data can be well fitted by the following function

$$\sigma_y^2(\tau)= 1.3\times10^{-20}\tau^{-1}+13\times10^{-18}+9\times10^{-16}\tau$$

(dashed line in Fig. 6). From this analytical behavior it is possible to recognize that the laser frequency noise is affected by three independent noise processes: a white frequency noise for integration times shorter than 1 ms (τ^{-1} term), a flicker frequency contribution from 1 ms to 10 ms integration time range, and a random walk frequency noise process for integration times longer than 10 ms (τ term). This combination of noise processes can also be expressed in terms of power spectral density of the frequency noise as the following polynomial function [12]:

$$S_{\Delta\nu}(f)=(9.5\times10^{12}f^{-2}+22\times10^{10}f^{-1}+6\times10^{8})\ \mathrm{Hz^2/Hz}$$

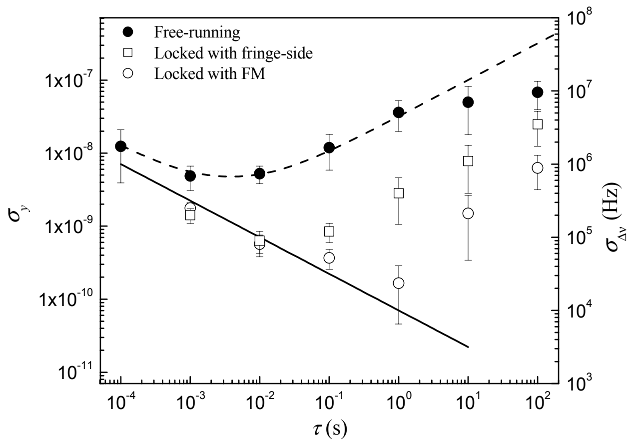

Figure 6. Allan standard deviation of the beat signal versus integration time τ. Lasers in free-running (filled circles); lasers stabilized using the fringe-side method (open squares); lasers stabilized using the FM spectroscopy method (open circles).

where f is the Fourier frequency around the laser carrier frequency.

The laser frequency instabilities were strongly reduced (Fig. 6) when the lasers were locked against the P(32) line of CO_2 by the fringe-side and the FM methods. In both cases the influence of the stabilization control loop was evident only for integration times longer than 1 ms (the control bandwidths were limited to 1 kHz) and a white frequency noise limit of $\sigma_y(\tau)= 6.7\times10^{-11}\,\tau^{-1/2}$ ($S_{\Delta\nu}(f)$=2×10^8 Hz^2/Hz) was reached (solid line in Fig. 6). When the fringe-side technique was used, however, the beat note showed a minimum frequency deviation of 100 kHz for integration times of 10 ms, whereas, in the case of the FM technique, a minimum frequency instability level of 20 kHz was obtained for 1 s integration time. For the same integration time of 1 s, the fringe-side technique shows frequency instability sixteen times higher. For longer integration times, the frequency stability was degraded by a random walk frequency noise and systematic effects (thermal drifts and optical feedback) in both the adopted configurations. The difference between the achieved stability levels indicates that the FM technique is more efficient than the simple fringe-side locking scheme for integration times longer than 10 ms, whereas in the short-term region, being the stability essentially limited by the signal to noise ratio of the frequency discriminator, there are no substantial differences in the achieved performance. This behavior is a direct consequence of the indirect (demodulation) detection exploited by the FM technique, which is intrinsically more insensitive to systematic effects than the simple direct detection. As a second general advantage over the fringe-side method, it is worth pointing out that the FM technique permits to stabilize the laser frequency to the center of the molecular resonance increasing in this way the frequency accuracy of the stabilized source.

V. Conclusions

Single-frequency diode-pumped Tm-Ho:YAG lasers, tunable in the 2085-2099 nm wavelength range, were frequency stabilized with respect to CO_2 rovibrational transitions. A comparison between two different frequency-locking techniques, the fringe-side and the frequency modulation methods, is reported using frequency measurements of the beat note between the two independently stabilized lasers. With both the adopted locking methods a significant improvement of laser frequency stability was obtained. In particular the minimum stability of 20 kHz at 1 s integration time was achieved using the FM method, whereas for the fringe-side method a minimum stability of 100 kHz was obtained for an integration time of 10 ms, indicating that the former technique is more efficient and should be adopted when medium- and long-term stability of the laser is the main concern.

References

[1] S. M. Henderson, C. P. Hale, J. R. Magee, M. J. Kavaya, and A. V. Huffaker, “Eye-safe coherent radar system at 2.1 µm using Tm-Ho:YAG lasers,” Opt. Lett. **16**, 773–775 (1991).

[2] T. M. Taczak, D. K. Killinger, “Development of a tunable, narrow linewidth, cw 2.066-µm Ho:YLF laser for remote sensing of atmospheric CO_2 and H_2O,” Appl. Opt. **37**, pp. 8460-8476, 1998.

[3] G. J. Koch, A. N. Dharamsi, C. M. Fitzgerald, J. C. McCarthy, “Frequency stabilization of a Ho:Tm:YLF laser to absorption lines of carbon dioxide,” Appl. Opt. **39**, pp. 3664-3669, 2000.

[4] J. E. Bernard, B. G. Whitford, and A. A. Madej, “A Tm:YAG laser for optical measurements: mixing 148 THz with CO_2 laser radiation,” Opt. Commun. **140**, 45–48 (1997).

[5] T. J. Kane, R. W. Wallace, “Performance of a diode-pumped Tm:Ho:YAG laser at temperatures between –55 and +20 °C,” in: Technical Digest, Conference on Lasers and Electrooptics, Washington, DC, Optical Society of America, 1988.

[6] S. L. Gilbert, “Frequency stabilization of a tunable erbium-doped fiber laser,” Opt. Lett. **16**, pp. 150-152, 1991.

[7] J. Rutman, F. L. Walls, “Characterization of Frequency Stability In Precision Frequency Sources,” IEEE Proc. **79**, pp. 952-960, 1991.