ABSOLUTE FREQUENCY STABILIZATION OF A Tm-Ho:YAG LASER TO $H^{79}Br$ TRANSITION AT 2097.2 nm AND CO_2 TRANSITION AT 2087.8 nm

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ABSTRACT

A compact diode-pumped Tm-Ho:YAG laser was fabricated and characterized, with emission wavelength tunable between 2085 and 2099 nm in single-frequency operation. High-resolution spectroscopy of several absorption lines of HBr and CO_2 was performed, and the laser was locked to the $H^{79}Br$ P(12) transition at 2097.222 nm and to the CO_2 P(22) transition at 2087.844 nm. The frequency stability level achieved was evaluated by monitoring the beat note between two oscillators, independently locked to the same molecular absorption. The frequency fluctuations were lower than 600 kHz (rms) over 1600 s with 20-Hz acquisition bandwidth. The Allan standard deviation for the beat frequency was 60 kHz for a 3-ms integration time.

Keywords: frequency stability, spectroscopy, frequency standards, Tm-Ho microlaser.

1. INTRODUCTION

Frequency-stabilized lasers emitting in the eye-safe spectral region near 2 µm are attractive sources for many applications, such as high-resolution spectroscopy, optical metrology, coherent Doppler wind velocimetry, and Differential Absorption Lidar (DIAL) measurements of carbon dioxide and water vapor contents in the atmosphere (see Refs 1-3). 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. 4) in the 2080 nm–2100 nm spectral region, where several transitions of carbon dioxide and water vapor are available. In this work we demonstrate the absolute frequency stabilization of a single-frequency Tm-Ho:YAG laser, recently developed by our group, to absorption lines of HBr and CO_2. The main novelties as compared to a previous work (Ref. 5) are the frequency locking to several transitions of two different molecules, whereas just one line and only one absorber was previously used; the improved stability level achieved; the more accurate analysis of the frequency stability by measurements of the beat note between two independently stabilized lasers. Our laser has a 3-mm thick active rod, longitudinally pumped by a 3-W GaAlAs laser diode emitting at 785 nm. Two intracavity etalons, 100 µm and 300 µm thick respectively, ensure single-mode operation and allow for coarse wavelength tuning (Ref. 5) in the 2087-2099 nm spectral range. Fine tuning of the emission frequency, within a cavity free-spectral range (~3 GHz), is achieved by an annular piezoelectric transducer (PZT) glued to the output mirror. We used a multipass absorption cell filled with the chosen gas species to perform high-resolution spectroscopy of molecular transitions; the fringe side locking technique [6] was used to lock the laser frequency to different resonances of HBr and CO_2.

2. HIGH-RESOLUTION SPECTROSCOPY

The first set of experiments was performed by using the P(12) rovibrational line of $H^{79}Br$, falling at 2097.222 nm, within a transmission window of the atmosphere. This circumstance can be particularly suitable for Doppler Wind velocimetry Lidar (DWL) applications, in which the absorption of the test beam in the atmosphere must be as low as possible. We used a 37-passes cell (path length 7.54 m), filled with HBr, to increase the peak absorption. The pressure was set to 10 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. Figure 1 shows a recording of the transmission spectrum: the full width at half maximum (FWHM) is 498 MHz and the peak absorption is 44%. Other absorption features of HBr was also measured, such as the P(11) doublet at ~2086 nm. In further experiments we used a 77-passes cell (path length

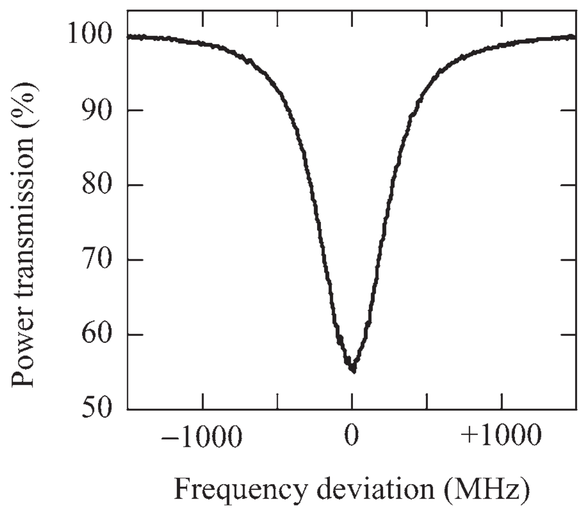

Fig. 1. Measured power transmission spectrum of the P(12) absorption line of $H^{79}Br$ at 2097.222 nm.

29.26 m) filled with CO_2 at 11 kPa pressure. Several absorption lines were measured, falling in the 2087-2095 nm spectral range. Figure 2 shows, as an example, the P(22) rovibrational line, located at

2087.844 nm: the measured FWHM is 1.28 GHz with a 77% peak absorption.

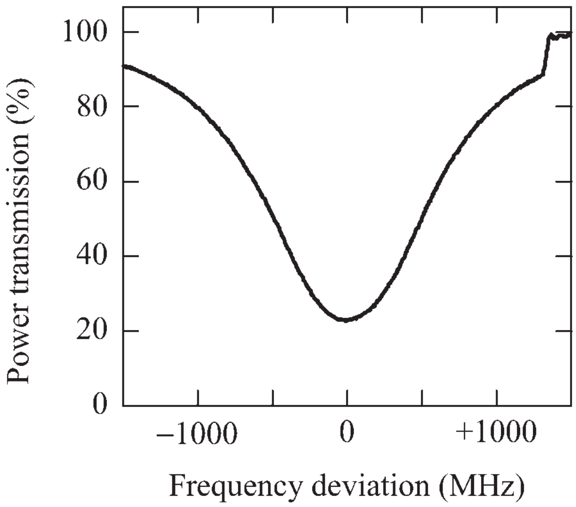

Fig. 2. Measured power transmission spectrum of the P(22) absorption line of CO_2 at 2087.844 nm.

3. FREQUENCY STABILIZATION

We locked the laser frequency to selected molecular 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. 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. In particular, we will show results achieved using the P(12) $H^{79}Br$ line at 2097.222 nm and the P(22) CO_2 line at 2087.844 nm. The transmission curves have comparable frequency discrimination power: the slopes, near the flex points, are 0.9 GHz^{-1} and 0.8 GHz^{-1}, respectively. The experimental setup used for frequency locking is shown in Fig.3: two Tm-Ho:YAG lasers were simultaneously stabilized, using the same multipass cell, to evaluate the achieved stability level by measuring the beat note. In the following we will focus our attention on the first one of the two frequency-locked laser systems. The currents detected by photodiodes PD1 and PD2 were balanced, using a variable optical attenuator (OA1), in correspondence of a flex point of the transmission curve. The difference between these photocurrents was sent to a transimpedance amplifier and was used as the error signal of the stabilization loop. A suitable feedback circuit was designed and fabricated to ensure high loop gain (~30 dB) at low Fourier frequencies and loop stability. The 0-dB crossing point is maintained at a frequency (~1 kHz) sufficiently lower than the first mechanical resonance of the PZT-mirror assembly (~3 kHz). The beat note between the two independently stabilized laser was monitored by a fast photodetector (PD5 in Fig. 3), 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(12) line of HBr, is shown in Fig. 4. 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. Comparable results were obtained also by using the P(22) CO_2 line at 2087.844 nm as the frequency discriminator for both lasers.

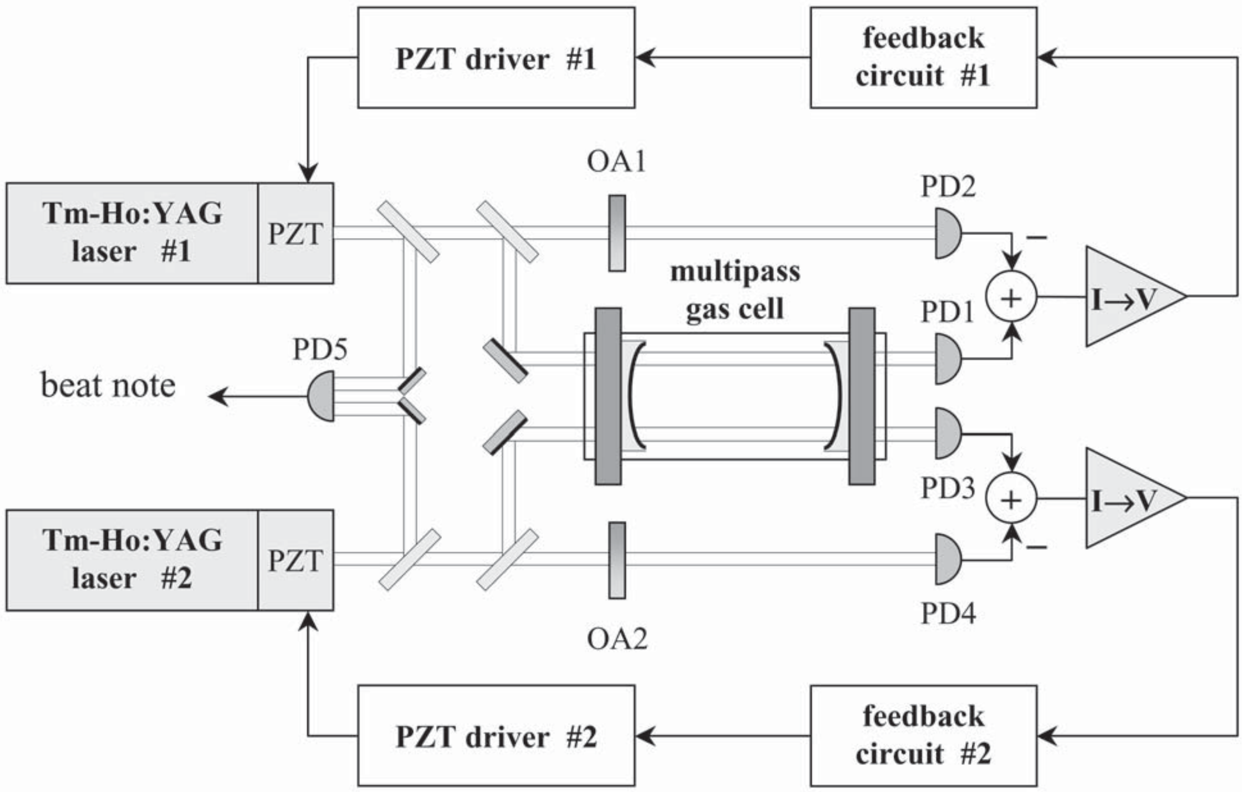

Fig. 3. Experimental setup for absolute frequency stabilization of two Tm-Ho:YAG lasers against the same molecular transition. I->V: transimpedance amplifiers.

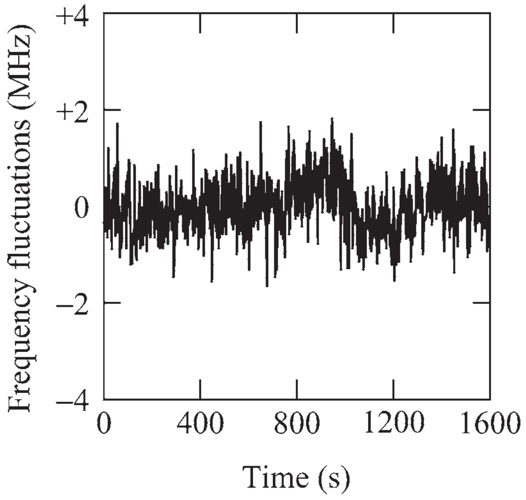

Fig. 4. Fluctuations of the beat frequency between the two lasers, independently locked to the P(12) absorption line of $H^{79}Br$ at 2097.222 nm.

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. 5; 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. The PSD curve was interpolated by polynomial analytical expressions, i.e., by segments of straight lines with different slopes in bilogarithmic scale, as shown in Fig. 5. Similar results were obtained also at 2097.2 nm: the PSD of the beat note is shown in Fig. 6, for both lasers locked to the P(12) line of $H^{79}Br$ (solid lines) and in free-running operation near 2097.2 nm (dotted line). The control

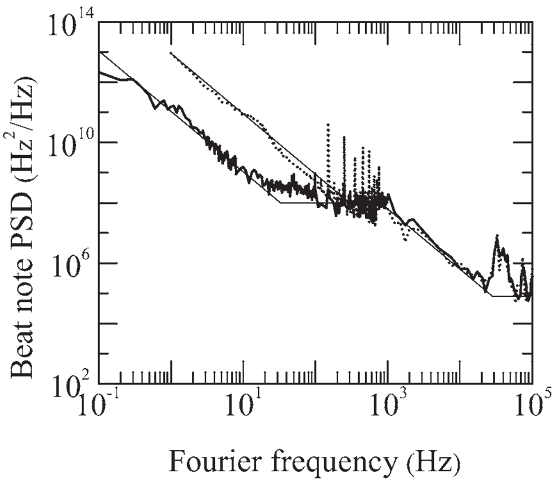

Fig. 5. Power Spectral Density of the beat frequency fluctuations with both lasers locked to the P(22) CO_2 line at 2087.844 nm (solid lines) and in free-running operation (dotted line).

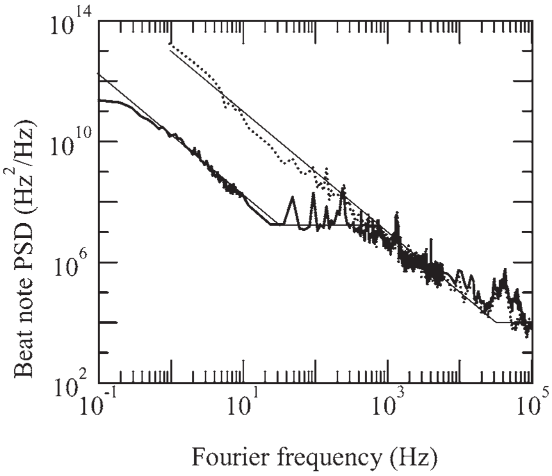

Fig. 6. Power Spectral Density of the beat frequency fluctuations with both lasers locked to the P(12) $H^{79}Br$ line at 2097.222 nm (solid lines) and in free-running operation (dotted line).

bandwidth of the stabilization loop is ~0.9 kHz in this case. The interpolating polynomial approximations of the spectra were used to calculate the Allan variance (see Ref. 7) of the beat frequency fluctuations. The corresponding two-sample deviation is shown in Fig. 7 as a function of the integration time, in the range between 1 μs and 1 s. By comparison with the dotted curve, corresponding to the unlocked condition, one can see that the stabilization loop effectively reduces the frequency noise for integration times higher than ~300 μs; the two-sample deviation presents a minimum of ~40 kHz at 10 ms and its value at 3 ms, corresponding to the round-trip time for a typical Lidar experiment, is reduced from 444 kHz to 60 kHz by frequency locking both lasers.

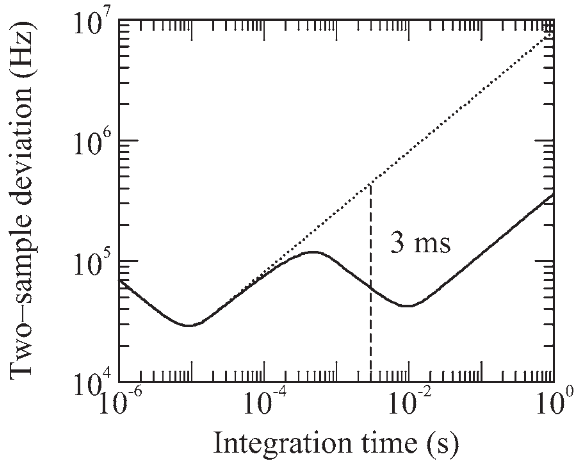

Fig. 7. Power Spectral Density of the beat frequency fluctuations with both lasers locked to the P(22) CO_2 line at 2087.844 nm (solid lines) and in free-running operation (dotted line).

4. CONCLUSIONS

Single-frequency diode-pumped Tm-Ho:YAG lasers, tunable in the 2085-2099 nm wavelength range, were designed and fabricated. High-resolution spectroscopy of several absorption lines of HBr and CO_2 was performed, and the lasers were successfully locked to HBr and CO_2 rovibrational transitions. The beat frequency between two independently stabilized lasers was used to evaluate the stability level, yielding a significant improvement achieved by the locking mechanism. This work could be useful for the development of a compact and all-solid-state Lidar system in the eye-safe spectral region near 2 μm.

5. REFERENCES

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