Frequency stabilization of a diode laser at 1540 nm by locking to sub-Doppler lines of potassium at 770 nm

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An external cavity 1540-nm diode laser was frequency doubled in a 3-cm-long periodically poled $LiNbO_3$ waveguide doubler with 150% W^{-1} conversion efficiency, thereby generating more than 3 μW at 770 nm. Second-harmonic light was used to detect and lock to sub-Doppler lines of the $^{39}K\ D_1$ transition. © 1998 Optical Society of America

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1. Introduction

Absolute frequency stabilization of lasers near the 1550-nm transmission window of optical fibers is required for several applications: frequency standards for wavelength division multiplexed systems,[1] coherent optical communication,[2] optical frequency synthesizers,[3] fiber-optic sensing,[4] and laser spectroscopy and metrology.[5] Numerous studies have been devoted to the absolute stabilization of 1550-nm lasers.[6] In most of these experiments, the locking was done to Doppler-broadened lines whose linewidth is relatively broad, i.e., several hundred megahertz. However, higher accuracy and stability frequency references require locking to narrower transitions. Locking to narrow sub-Doppler lines of C_2H_2 and HCN was recently demonstrated by de Labachelerie *et al.*[7] However, since the saturation intensity of $^{13}C_2H_2$, for example, is 18 W/mm^2 at a pressure of 0.1 Torr, a Fabry–Perot enhancement cavity was employed to achieve sufficient power for saturation spectroscopy of these weak molecular lines. Another possibility is to lock to sub-Doppler optogalvanic lines of noble gases[8] or to optically pumped Rb lines,[9] but these methods require additional excitation, either optically or electronically.

An alternative approach for frequency stabilization is second-harmonic generation (SHG) and locking to sub-Doppler transitions of atomic lines, as we have recently demonstrated with the rubidium D_2 lines near 780 nm.[10] This method is not limited only to rubidium and in this paper we explore the potassium $^{39}K\ D_1$ line at 770.1 nm. The absolute frequency and frequency shift mechanism of the rubidium lines are known[11] to a higher accuracy than those of potassium, but the 1540-nm operating wavelength of a potassium-based system is closer to the gain center of Er-doped fiber amplifiers. Frequency doubling of a 1540-nm diode laser in bulk $KNbO_3$ was previously used by Wang *et al.*[12] to lock to a different isotope of potassium, ^{41}K; however, since only 20 nW were generated at the second harmonic, another pump laser at 770 nm was required for sub-Doppler spectroscopy. With the more efficient doubling technique that we used in this study, only a single frequency-doubled laser is required.

The saturation intensity of the atomic transitions of Rb and K is very small, i.e., several tens of microwatts per square millimeter. Nevertheless, efficient frequency doubling is required to obtain a sufficiently powerful second-harmonic signal from low-power single-frequency diode lasers at 1.5 μm. A key technology that enables one to reach the required efficiency is quasi-phase-matched (QPM) frequency conversion in a $LiNbO_3$ waveguide. In QPM doubling, a periodic modulation of the material nonlinear coefficient compensates for the phase velocity mismatch between the fundamental and second-harmonic waves. This technique permits the use of the large diagonal elements of the $\chi^{(2)}$ tensor that cannot be used with birefringent phase matching. In $LiNbO_3$, the QPM frequency-doubling efficiency can be as much as a factor of 20 higher than the birefringent phase-matching doubling efficiency. Further improvement in conversion efficiency is ob-

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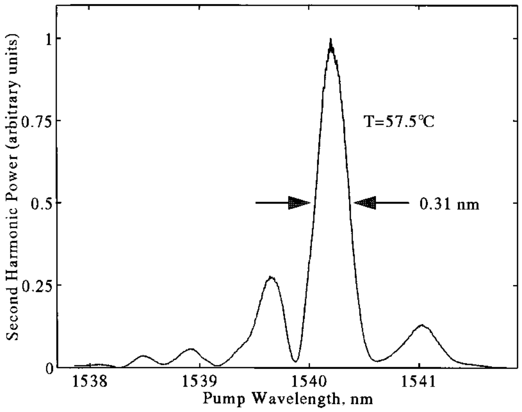

Fig. 1. Generated second-harmonic power in the periodically poled $LiNbO_3$ waveguide doubler as a function of the fundamental wavelength.

tained by waveguide confinement. Compared to confocally focused bulk interactions, the waveguide improvement factor scales as $\lambda L/2n_\omega A_{\mathrm{eff}}$, where λ and n_ω are the fundamental wavelength and refractive index, respectively, and L and A_{eff} are the waveguide length and cross-sectional area, respectively.

2. Experimental Setup and Results

The frequency doubler we used was a periodically poled $LiNbO_3$ waveguide. The channel waveguide device was 3 cm long and dual mode at the 1540-nm input wavelength. Pump light was coupled into the fundamental mode of the waveguide. The periodic modulation of the nonlinear coefficient with a period of 14 μm was achieved by electric field poling and the waveguide was fabricated by annealed proton exchange, as described in detail elsewhere.[13] Figure 1 shows the second-harmonic power generated by the waveguide doubler as a function of the fundamental wavelength. The pump laser was a tunable external cavity diode laser, New Focus Model 6262. The single-pass efficiency for SHG of 1540.2 nm in the waveguide was 150% W^{-1} with a FWHM bandwidth of ≈0.31 nm. The wavelength of the peak second-harmonic efficiency could be slightly tuned with temperature. The waveguide device was maintained at a temperature of 57.5 °C in order to match the potassium line. With 1.4 mW at 1540 nm coupled into the waveguide we obtained 3 μW at 770 nm in the fundamental mode of the waveguide. This power level is 150 times higher than the level achieved by bulk SHG.[12] The doubler output face was polished at a 15-deg angle with respect to the waveguide in order to avoid etalon effects that caused wavelength-dependent output power fluctuations observed in a previous doubling experiment at 1560 nm.[10]

The experimental setup for locking the laser is shown in Fig. 2. The laser light passed through an optical isolator (75-dB reverse isolation) and was injected into the waveguide doubler. The second-harmonic light passed through a 7.5-cm K cell that was held inside a Plexiglas tube and was heated using two heater tapes that were wrapped around its input and output windows in order to increase the vapor pressure. The isotopic mixture in the cell was a natural mixture: 93.1% of ^{39}K and 6.88% of ^{41}K. A thermocouple was used to monitor the cell temperature. Figure 3 shows the single-pass transmission signal through the cell at different cell temperatures. The main broadening mechanism in these measurements was the Doppler broadening that was ≈770 MHz at room temperature. The vacuum wavelength at line center was determined by a Burleigh WA20-DL wavemeter to be 770,110 ± 1 pm, in good agreement with that reported in Ref. 12.

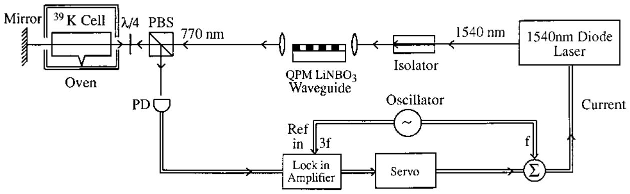

Fig. 2. Experimental setup for locking the external cavity laser to potassium sub-Doppler lines: PD, photodetector; PBS, polarizing beam splitter.

Sub-Doppler spectrum was obtained by double passing the SHG light through the cell. The beam diameter inside the cell was ≈0.4 mm and the intensity was ≈20 $\mu W/mm^2$. The frequency was dithered using the laser current at a frequency of 1.3 kHz and the third-harmonic component at 3.9 kHz was measured using a lock-in amplifier. The sub-Doppler spectrum of ^{39}K $4S_{1/2} \rightarrow 4P_{1/2}$ transition at a cell temperature of 39 °C is shown in Fig. 4. The measured linewidths of the transitions were ≈9 MHz. It is also possible to observe the weak ^{41}K $4S_{1/2} \rightarrow 4P_{1/2}$ transitions ($F'' = 2 \rightarrow F' = 1, 2$ and $F'' = 1 \rightarrow F' = 1, 2$, labeled I and II, respectively). All the other unlabeled transitions are ^{39}K crossover transitions. Some of the ^{41}K crossover transitions fall near the *c* transition of ^{39}K and hence cannot be resolved. The frequency splitting of the ^{39}K $4S_{1/2}$ and $4P_{1/2}$ transitions[14] (462 and 55.6 MHz, respectively) is wider than that

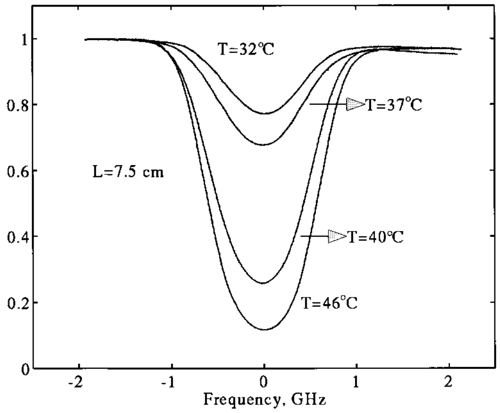

Fig. 3. Normalized transmission through a 7.5-cm potassium cell at different cell temperatures.

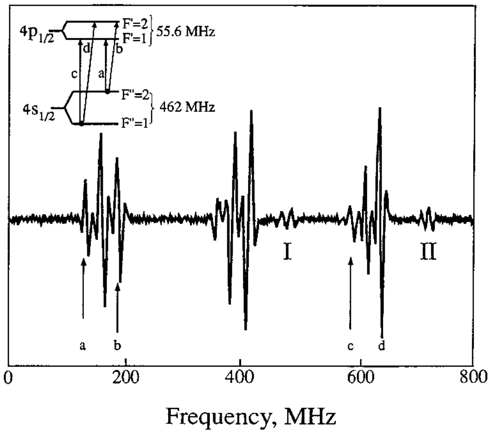

Fig. 4. Sub-Doppler spectrum of the potassium D_1 transition. The unlabeled strong transitions are crossover lines, and the weak lines (labeled I and II) are ^{41}K transitions. Lock-in time constant: 10 ms. The inset shows the energy levels of ^{39}K.

for ^{41}K lines (254 and 30.4 MHz, respectively). Thus, the ^{39}K sub-Doppler lines are easier to separate and therefore better candidates for frequency stabilization than the ^{41}K lines.

We have locked the laser to the a/b crossover line by feeding the output of the lock-in amplifier, through a servo controller, back to the laser current. The signal-to-noise ratio obtained with this line, see Fig. 4, is ≈50 with a 10-ms time constant. The servo controller open loop gain G as a function of frequency f was $\sim 500/f$. A time trace of the error signal when the laser was locked is shown in Fig. 5(a), with 10-ms integrating time per measurement point. The frequency fluctuations are below 100 kHz. The free running laser frequency typically drifts in this time scale by several megahertz.[10]

We have also measured the power spectral density of the error and actuator signals; see Fig. 5(b). These signals were converted to frequency units by multiplying with the slope (in hertz per volts) of the a/b crossover line or dividing by the laser frequency modulation response (in volts per hertz), respectively. The error signal is essentially the frequency noise density of the locked laser. Since the actuator signal compensated for the drifts of the free running laser from the potassium transition frequency, for servo open-loop gain $G \gg 1$ (up to ≈500 Hz in this measurement), the actuator signal is nearly identical to the frequency noise spectral density of the free running laser. Figure 5(b) therefore indicates that the free running frequency noise was indeed suppressed considerably by the servo at low frequencies. Owing to the 1-ms time constant of the lock-in amplifier used in this measurement, the signals rolled off at 20 dB/decade for frequencies higher than $1000/2\pi \approx 160$ Hz. The laser current was modulated in this case at a frequency $f = 1.8$ kHz in order to provide the required $3f$ sub-Doppler signal, and this resulted in the appearance of peaks at the harmonics of this frequency in the two curves of Fig. 5(b).

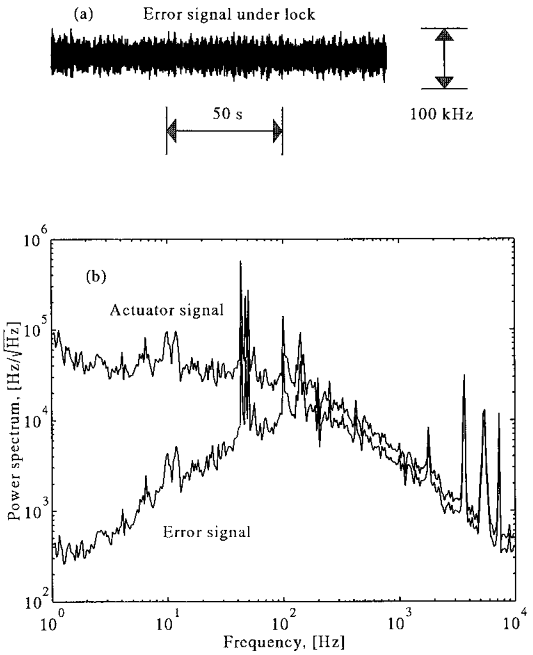

Fig. 5. (a) Time trace of the error signal frequency variations at 1540 nm while the laser was locked to the a/b crossover line. (b) Power spectral densities of the error and actuator signals.

3. Summary

We have demonstrated locking to the relatively narrow and well-resolved sub-Doppler lines of ^{39}K using a single-frequency doubled 1540-nm diode laser. The ^{39}K isotope was found to be a better candidate than ^{41}K for frequency stabilization of the laser, owing to the wider splitting of the hyperfine levels. Most of the laser power at the fundamental frequency remained useful for applications because only a small fraction of it was frequency doubled to stabilize the frequency. The advantages of locking to sub-Doppler resonant atomic lines, rather than to Doppler-broadened lines, include improved frequency stability and reproducibility. Furthermore, in locking schemes that require dithering of the laser frequency, the dither span, which is of the same order as the absorber linewidth, is much smaller when sub-Doppler lines are used. Owing to the low saturation intensities of atomic lines and the high doubling efficiency, sub-Doppler lines are obtained by standard saturation spectroscopy techniques, and a Fabry–Perot enhancement cavity[7] is not required.

The method of efficient QPM frequency doubling in a waveguide and locking to absorption lines at the second harmonic can also be applied at the 1300-nm transmission window of optical fibers and was previously used to lock a frequency-doubled 1319-nm Nd: YAG laser to molecular lines of I_2.[15] At the 1550-nm band another possibility is to lock a frequency-doubled laser to the Rb two-photon absorption at 778 nm.[16] In addition, the potential frequency standards we have investigated so far at 1560.5 and 1540.1 nm are 2.5 THz apart and hence can be used to calibrate transfer standards, e.g., a Fabry–Perot.

Finally, the small physical size of the frequency doubler and sealed absorption cell could enable the realization of compact, portable, and high-performance frequency standards for wavelength division multiplexed optical communication and fiber-optic sensing systems.

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