Frequency Stabilization of a Novel 1.5-μm Er–Yb Bulk Laser to a ^{39}K Sub-Doppler Line at 770.1 nm

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***Abstract*—The second harmonic output at 770.1 nm of a novel and compact Er–Yb:glass laser was frequency stabilized against the sub-Doppler linewidth of a crossover line in the ^{39}K $4S_{1/2}$-$4P_{1/2}$ transition as obtained by saturation spectroscopy. Efficient frequency doubling, with a conversion efficiency of $\sim$220% W^{-1}, and with second harmonic power in excess of 15 μW, was achieved in a waveguide made in a periodically poled lithium niobate crystal. As measured through the analysis of the closed-loop error signal, a laser frequency instability of $\sim$200 Hz was obtained; the Allan standard deviation of the frequency samples was below 4×10^{-12} for integration times τ between 100 ms and 100 s, and reached a lowest floor level of 8×10^{-13} for 20 s $\leq \tau \leq$ 100 s. The measured frequency noise spectral density was in good agreement with the analysis performed in the time domain. Compared to previously published data for stabilized solid-state laser sources in this wavelength region, these results represent a significant improvement in the frequency stability.**

***Index Terms*—Erbium, frequency conversion (doubling), frequency stability, solid (state) laser, 1.5-μm, potassium.**

I. Introduction

LASER frequency stabilization in the 1.5-μm spectral region is of great interest for optical fiber communication systems [1], [2] for metrology applications in the near infrared, for optical fiber sensors [3], and for high-resolution spectroscopy. For all these applications, the achievement of absolute frequency reference lines in this spectral region is intensively pursued. Several studies have been indeed devoted to absolute frequency stabilization of 1.5-μm semiconductor lasers against atomic [4]–[6] or molecular [7]–[9] absorption lines. Diode lasers, however, exhibit relatively poor spectral and spatial qualities of the output beam, even when used in an external-cavity configuration, when compared to solid-state lasers. Diode-pumped bulk Er–Yb lasers oscillating at 1.5 μm [10], on the other hand, are very attractive sources for amplitude [11] and frequency stabilization [12] due to their intrinsic stability, wide wavelength tunability [13], high optical power, and excellent beam quality. Recently, this kind of laser was frequency locked against different Doppler-broadened molecular lines of acetylene in the 1.5-μm spectral region by means of both fringe-side locking [14], [15] and an FM-sidebands [16] technique. The frequency instability was, however, limited to the $10^{-9} \div 10^{-10}$ level due to both the relatively broad linewidth of the reference line and to the intrinsic stability and reliability of the laser source.

In this paper, we first report on a novel Er–Yb:glass microlaser with significantly improved stability and reliability performance [17]. The primary novelties are related to a very compact, massive, and hermetically sealed-off design of the laser cavity and to the use of a fiber-coupled diode laser pump. These innovations resulted in a large reduction of the frequency noise of the free-running laser as arising from temperature and pressure changes and, in particular, from acoustic vibrations of the cavity. The 1.5-μm output beam was then frequency doubled, in an efficient way, in a periodically poled lithium niobate (PPLN) waveguide doubler. The resulting second-harmonic beam was frequency locked, by the wavelength-modulation technique, to a ^{39}K sub-Doppler line at 770.110 nm. Short- and medium-term frequency stability were derived from the control-loop error signal. The measurements revealed two orders of magnitude improvements in the root Allan variance as compared to the previous experiments performed with these lasers and C_2H_2 Doppler-broadened lines. High-resolution spectroscopy of the ^{39}K low-pressure atomic sample was also achieved where the narrow linewidth of the laser source enabled clear determination of all the saturation dips and crossover lines corresponding to the hyperfine structure of the $4S_{1/2}$-$4P_{1/2}$ transition in this atom.

II. Er–Yb Laser

A novel diode-pumped Er–Yb:glass microlaser with a compact, massive, and sealed-off design has been developed [17]. The ruggedness and compactness of the laser design was further improved with the use of a fiber-coupled diode laser at 978-nm wavelength as the pump source. In this way, a single-frequency output power at 1.5 μm up to 20 mW was obtained and the output beam was in the diffraction-limited TEM_{00} mode. Furthermore, higher long-term stability and consistent suppression of the frequency noise for the free-running laser, e.g., due to acoustic vibrations, were obtained. The laser was continuously tunable over a 17-nm range around the central wavelength of 1539 nm, while piezoelectric control of the optical cavity length enabled fine frequency control. In particular, the use of a phosphate glass host for the active Er^{3+} ions allows for very broad and continuous wavelength tunability in the 1.55-μm spectral region [13].

A schematic drawing of this Er–Yb laser is shown in Fig. 1. The active medium consists of a 1mm thick $\times 3 \times 3$ mm^2 wide square platelet, made of a special phosphate glass (Kigre Inc.,

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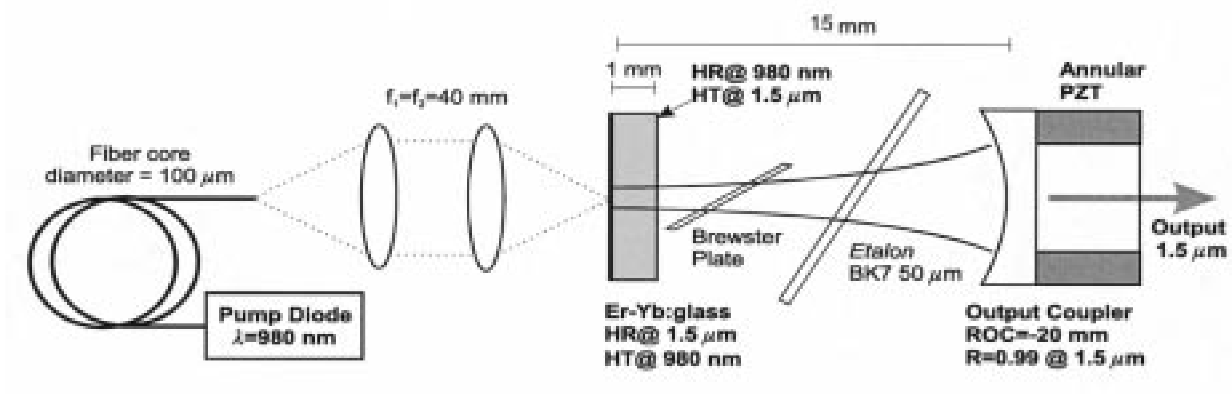


Fig. 1. Schematic diagram of the diode-pumped Er–Yb:glass laser.

QX/Er) doped with Er^{3+} at 0.73×10^{20} ions/cm^3 and Yb^{3+} at 1.9×10^{21} ions/cm^3. The pump radiation was obtained from a 1-W 980-nm laser diode coupled to a 100 μm core and 0.13-NA optical fiber (Opto Power Corporation, H01-A001-FC/100). Two spherical lenses provided for a 1:1 imaging of the pump beam in the active medium. The optical cavity consisted of a plano-spherical resonator of ∼16-mm optical length: the input mirror was dielectrically coated onto the active medium (R >99.9% power reflectivity at 1.5 μm and T >96% power transmission at 978 nm) and the output coupler was made of a spherical mirror with radius of curvature $R = -20$ mm and transmission at the laser wavelength of 1%. The second facet of the active medium, inside the laser cavity, was antireflection coated at the laser wavelength ($R < 0.2$% at 1.5 μm) and with a high reflectivity at the pump wavelength (R >94% at 978 nm). This back reflection of the unabsorbed pump power resulted in double-pass pumping, allowing for a uniform and significant population inversion along the Er–Yb phosphate glass (see Fig. 2). In fact, for these quasi-three-level lasers [18], [19], it is very important to avoid unpumped regions within the active medium, which would otherwise result in reabsorption losses. Furthermore, due to a rather poor thermal conductivity of the phosphate glass used (∼0.85 Wm^{-1}K^{-1}), severe damage problems arise at relatively low pump power levels when a nonuniform pumping profile is employed. It was observed, in fact, that even under our more uniform pump conditions, pump powers in excess of ∼500 mW could produce permanent damage (cracks) in the laser platelet as a consequence of excessive local heating and thermal gradients within the glass host.

Single longitudinal mode selection was obtained by inserting within the laser cavity a 50-μm glass etalon, coated for a reflectivity of 10% at the laser wavelength. The selection of a specific wavelength, within the etalon-free spectral range of 17 nm, was achieved by fine tilting the etalon away from normal incidence. The output mirror was mounted on an annular piezoelectric transducer (PZT) to allow fine-tuning of the laser frequency by means of a voltage control signal. The PZT we used (Pickelmann, HPSt-500/10-5/15) provided a $\lambda/2$ excursion with a control signal of 32 V. The mode-hop-free frequency tuning range was 9.7 GHz with a tuning coefficient $K_{\rm PZT}$ =290 MHz/V. This frequency span, combined with the continuous wavelength tunability achievable upon tilting of the etalon, was wide enough

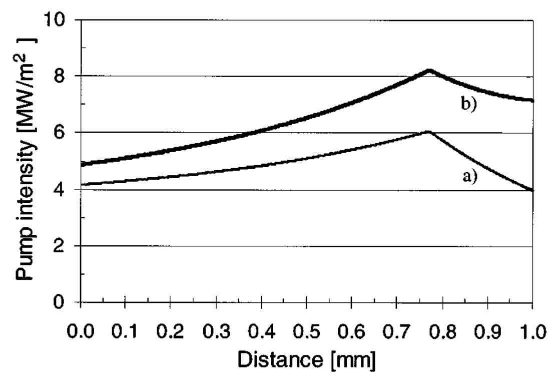


Fig. 2. Pump intensity profile within the 1-mm thick active medium: (a) single-pass pumping condition and (b) double-pass pumping condition. The distance on the horizontal axis is calculated from the input mirror.

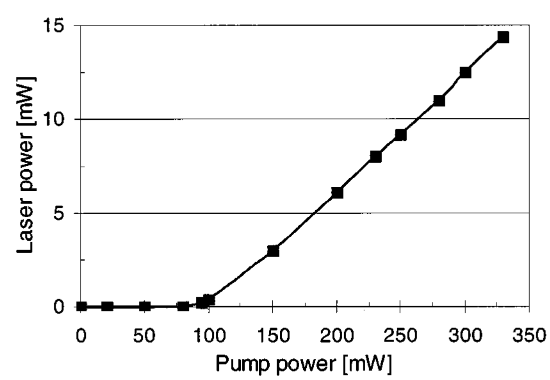


Fig. 3. Single-frequency output power at 1.5 μm as a function of the incident pump power.

for performing high-resolution laser spectroscopy of different molecular/atomic transitions falling in this spectral region. By properly mode matching the pump beam to the laser beam in the active medium, oscillation on the fundamental TEM_{00} transverse mode was achieved without the need for intracavity pinholes, and a quite efficient laser action is obtained (see Fig. 3). During our experiment, the threshold pump power for this laser was 95 mW and the slope efficiency was 6%, in single-frequency operation. The typical oscillation linewidth was below 50 kHz in 1 ms. The maximum laser output power was kept below 8 mW due to the choice of working within a very safe pump power level of 230 mW. From our experience, an upper limit to the pump power in our working conditions (pump spot size of $\sim$100 μm diameter) lies in the 400–600 mW range depending on the residual stress and tensions left in the phosphate glass after the cutting and polishing processes. New strengthened glasses, already produced by Kigre Inc., should enable one to increase the rupture strength by a factor of three, thus allowing for much higher pump powers, and hence, laser outputs in the range of 50 mW. Actually, single-frequency output powers of slightly more than 50 mW have already been demonstrated, even using the unstrengthened glasses. Unfortunately, permanent damage in this glass is very likely to occur under these high pump powers.

It is interesting to compare the intrinsic stability of this discrete linear-cavity laser design to that of a widely used frequency-stable laser, namely the monolithic nonplanar ring oscillator. The short-term frequency stability of this Er–Yb:glass laser ($\sim$50 kHz at 1 ms) is slightly worse than that of the monolithic cavity ($\sim$10 kHz at 1 ms). However, due to the low gain of this quasi-tree-level active medium and to the large gain bandwidth of the Er^{3+} ion in the glass host (approximately 30 times wider than that of Nd:YAG at 1064 nm), it seems unpractical to realize a single-frequency tunable source with this material using the nonplanar ring design.

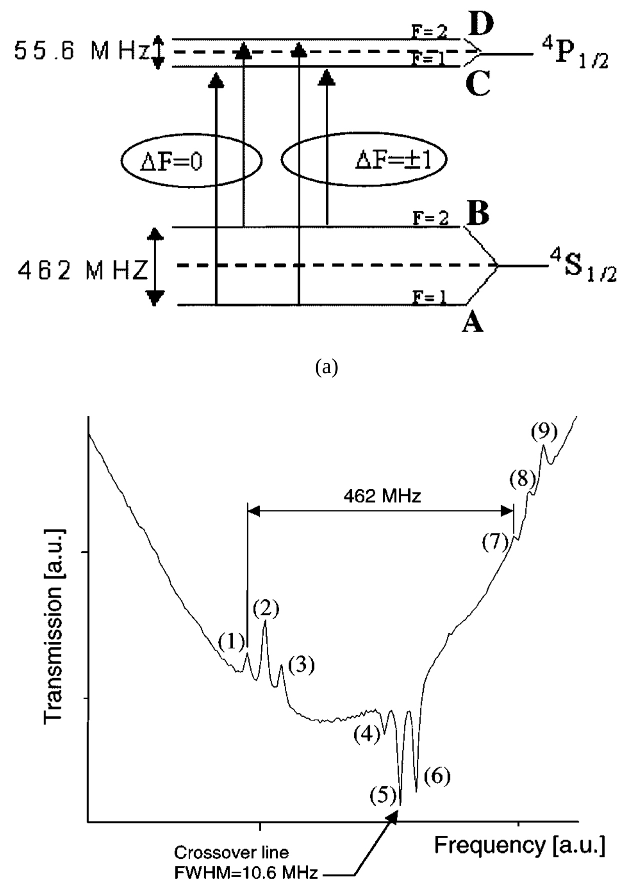
III. Frequency Doubling

To frequency double our 1.5-μm laser beam, we used a 30-mm long, $2.5\ \mu$m $\times$ $4\ \mu$m wide annealed proton exchange channel waveguide made in a PPLN crystal described in [20]. To this purpose, the circular output beam from the Er–Yb laser was first passed through an optical isolator (Optics For Research, IOT-4-1550, with >60-dB isolation) to avoid feedback to the laser cavity from the uncoated input face of the crystal. The transmitted beam from the isolator was then coupled into the PPLN waveguide by a microscope lens with a focal length of 4.5 mm. Quasi-phase-matched doubling at a wavelength of 1540.2 nm was achieved by keeping the waveguide doubler at a temperature of $62 \pm 1\,^\circ$C. The measured second harmonic power was 17 μW, and the external conversion efficiency was, therefore, 26% W^{-1}. Taking into account the losses owing to the coupling to the waveguide (approximately 50%), the Fresnel reflections of the input (14%) and output (20%) beams, and the losses in the waveguide ($\sim$20%), the internal second harmonic efficiency was $\sim$220 W^{-1}. This conversion efficiency was 2–3 orders of magnitude higher than the efficiency obtained in bulk frequency doublers. It should be noted, however, that with the potentially high power that can be generated with Er–Yb lasers, bulk frequency doublers may also be used. For example, assuming a pump power of 50 mW and a bulk conversion efficiency of 1% W^{-1} (which can be obtained with a 1-cm long PPLN crystal under optimal focusing conditions [21]), the generated second harmonic power is 25 μW. This power level is more than sufficient for saturated-absorption spectroscopy of resonant atomic lines such as the D_1 line of potassium or the D_2 line of rubidium. However, with the currently available laser power level, high efficiency schemes are required. In this respect, the waveguide doubler provides high efficiency in a simple single-pass scheme, and saves the complexity of locking the laser to a build-up cavity.

IV. Atomic Frequency Reference

To achieve narrow saturated transition with comparatively low saturation intensity, atomic absorptions are typically preferable with respect to molecular ones [22]. In particular, the second harmonic of 1.5-μm semiconductor lasers has been successfully used by different groups either to probe the saturated Rb [23]–[25], [31]or K [26], [6] lines or to frequency lock to these lines. The saturation intensity for these atomic transitions, whose wavelengths fall in the range from 770 to 780 nm, is much lower than the corresponding values for molecular absorptions at the fundamental wavelength. In particular, saturation spectroscopy of the $4S_{1/2} \rightarrow 4P_{1/2}$ ^{39}K transition at 770.110 nm can be achieved with an intensity of less than 100 μW/mm^2 [6] while the saturation intensity of the $^{13}C_2H_2$ molecule in the 1.55 μm band, even at a low gas pressure of 0.1 torr, is as high as 18 W/mm^2 [27], [28]. In our experiment, we therefore chose to use the ^{39}K atomic reference because the corresponding fundamental wavelength ($\sim$1540 nm) could be obtained with reasonably high power ($\sim$8 mW) with our newly developed Er–Yb microlaser. The K cell contained the natural mixture of 93.1% ^{39}K and 6.9% ^{41}K and was heated to 40 °C in order to increase the vapor pressure to $\sim 9 \times 10^{-8}$ torr, i.e., nearly a factor of 6 increase as compared to the corresponding value at room temperature [29]. Using the second harmonic beam generated in our PPLN waveguide, we produced a nearly collimated beam with a diameter of $\sim$200 μm within the K cell at a power level of $\sim$17 μW; sub-Doppler spectroscopy of the ^{39}K line was then performed by a standard pump and probe technique.

To carry out these spectroscopic measurements, the laser wavelength was set in proximity of the absorption line by tilting the intracavity etalon and, subsequently, sweeping of the laser frequency through the atomic resonance was achieved by ramping the voltage applied to the PZT frequency actuator. It was found that approximately 4 V of ramp amplitude was needed to fully scan the Doppler-broadened K line, whose full-width at half-maximum (FWHM) is $\sim$1.7 GHz. The optical power transmitted through the K cell was then detected by a photodetector and recorded with a digital scope. Fig. 4 shows one of the recorded spectral measurements of the ^{39}K line, under saturated absorption conditions. The absorption dips within the Doppler profile [see Fig. 4(b)] correspond to the different transitions between the four hyperfine structure levels of the $4S_{1/2}$-$4P_{1/2}$ transition [see Fig. 4(a)]. The three absorption dips to the left of Fig. 4(b) are due to the transitions between sublevels B–C (1) and B–D (3) and the corresponding crossover (2) due to the pump and probe process. The three absorption dips to the right of Fig. 4(b) are due to the transitions between sublevels A–D (9) and A–C (7) and the corresponding crossover (8). The three absorption peaks close to the line center are due to crossovers between transitions (1)–(7) (labeled 4), (3)–(9) (labeled 6) and between the intermediate “levels” [dashed lines in Fig. 4(a)] corresponding to a photon energy



(a)

(b)

Fig. 4. (a) Hyperfine structure levels of the $4S_{1/2}$-$4P_{1/2}$ transition of potassium. (b) Saturation spectroscopy of the ^{39}K sample as obtained by scanning the Er–Yb laser frequency through the Doppler resonance.

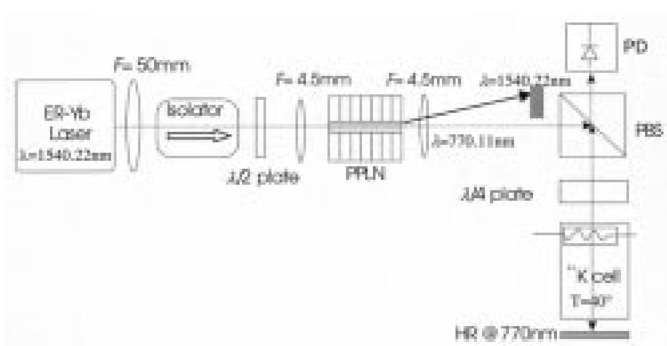


Fig. 5. Schematics of the experimental setup for frequency locking the Er–Yb laser to the ^{39}K sub-Doppler line. PD: silicon photo detector. PBS: polarizing beam splitter.

$hv = [(E_D + E_C)/2 - (E_B + E_A)/2]$. The crossover line (5) shows the best contrast, with a linewidth of ~10.6 MHz, and is indeed the one we chose for locking the laser wavelength. Its contrast, compared to the depth of the Doppler-broadened line, is found to be 16% with the available laser beam intensity of $\sim 540\ \mu$W/mm^2.

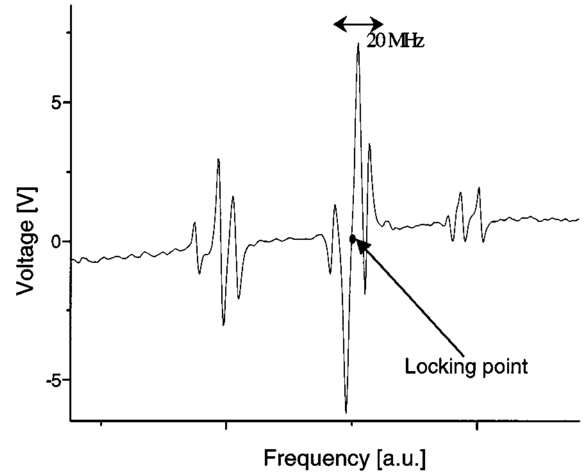


Fig. 6. First derivative voltage signal as obtained at the lock-in output after amplification of 50 V/V.

V. Wavelength-Modulation Spectroscopy and Frequency-Locking Experiment

The frequency-locking experimental setup is shown in Fig. 5. Using wavelength-modulation spectroscopy and synchronous detection, the first derivative of the signal corresponding to the crossover line of interest, i.e., line (5) in Fig. 4(b), was recorded. This voltage signal shows an odd symmetry with respect to the resonant frequency, and was used to lock the laser frequency to the central frequency of the crossover line. In our experiment, the modulation was superimposed to the laser frequency by feeding a sinusoidal voltage directly to the PZT. This saved the need for an external phase modulator and enabled the realization of a compact and simple locking system. The piezo bandwidth is lower than 1 kHz; hence, a sine-wave modulation at a frequency $f_m = 423$ Hz was used. With a voltage amplitude of 5 mV, we obtained a modulation frequency deviation of 2.9 MHz on the frequency-doubled laser beam, corresponding to a modulation index $\beta \cong 6850$. A lock-in amplifier (Stanford Research Systems, SR830) was used after the photodetector in order to retrieve the first and third derivative output signals. A lock-in sensitivity of 500 μV and a time constant of 3 ms, corresponding to a rolloff frequency of 53 Hz, were used during both wavelength-modulation spectroscopy measurements and frequency locking. The obtained first derivative signal, amplified by a factor of 50 V/V, is shown in Fig. 6. The measured linewidth of the crossover line was ~10.6 MHz (FWHM) and the slope of the derivative signal out of the lock-in amplifier, again amplified by a factor of 50, was 2.16 μV/Hz. While the third harmonic derivative signal provided improved suppression of the Doppler background, the signal-to-noise ratio was substantially lower in this case. Henceforth, despite the nonzero bias, the first derivative voltage of Fig. 6 was used as the frequency discriminator for the frequency-stabilization loop.

In order to lock the laser frequency to the crossover line, the first derivative signal was sent to an electronic servo (PI) and fed back to the laser PZT in a standard frequency-control loop. As a servo control circuit, we used a simple integrative circuit. The overall open-loop gain was measured to be 200 at 1 Hz (see Fig. 7). An additional zero was introduced in the

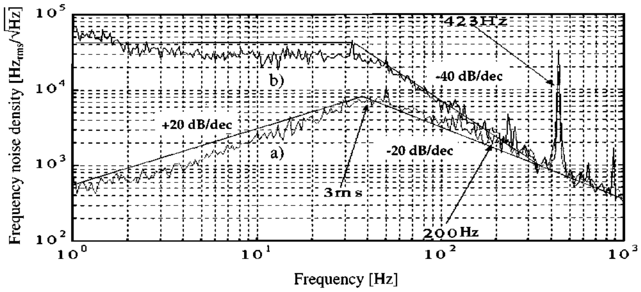


Fig. 7. Frequency noise spectral densities of the (a) closed-loop error and (b) control signals.

servo at the frequency of 53 Hz in order to compensate for the phase shift induced by the pole of the lock-in at this frequency; thus, the overall open-loop gain, given by to the product of the discriminator, controller, lock-in and piezo actuator transfer functions was $\sim 200/f$, where f is the frequency in Hertz. This value was confirmed by independent measurements of each one of these elements. Both the control and error signals were analyzed in the frequency domain, as shown in Fig. 7, revealing a significant frequency noise reduction at Fourier frequencies below 50 Hz. The change in slope for the error and control signal near 53 Hz is caused by the pole introduced by the lock-in amplifier and the phase compensating zero introduced by the servo. The resonance at 433 Hz is caused by the modulation of the laser frequency. In addition to spectral analysis, the laser frequency stability was evaluated by direct monitoring of the control-loop error signal in the time domain. The laser was kept locked to the potassium transitions for an arbitrary long time (more than 25 min in the recorded experiments) and with a peak-to-peak instability always below 100 kHz. The amplified closed-loop error signal obtained with a first derivative slope of 2.16 μV/Hz is shown in Fig. 8. The offset level in the recorded voltage signal is due to the electronic offset of the additional amplifier inserted between the error signal point and the digital scope used to monitor the signal fluctuations. Of course, the error signal itself is centered on the 0-V level as confirmed by maintenance of the lock condition. From the data of Fig. 8, the resulting peak-to-peak instability is $\sim$40 kHz over a 200-s observation period. By calculating the Allan variance of these frequency fluctuations at different integration times, a fractional frequency instability better than 4×10^{-12} was obtained for observation times between 100 ms and 100 s (see Fig. 9), reaching the lowest floor level of 4×10^{-13} for the integration times longer than 30 s. We note that these values represent a lower limit on the frequency instability, since they do not reflect the noise introduced by the discriminator itself. Full characterization of this system as a frequency reference requires a beatnote measurement against a second independent system. However, the results indicate that using the experimental scheme that was presented here, the laser can be tightly locked to the atomic transition. Furthermore, the excellent qualities of atomic sub-Doppler atomic lines as frequency references are well documented in numerous publications. For example, stability at the kilohertz level has been measured (using an independent frequency reference) for a frequency-doubled diode laser locked to sub-Doppler Rb lines near 780 nm. Given the higher second harmonic power and the improved spectral

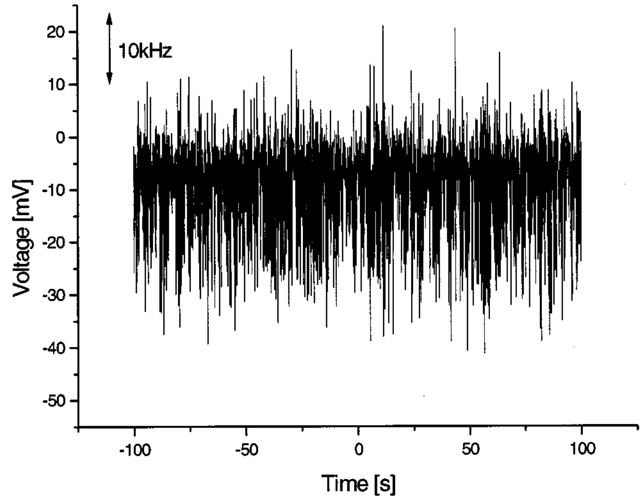


Fig. 8. Time analysis of the frequency fluctuations as observed from the closed-loop error signal.

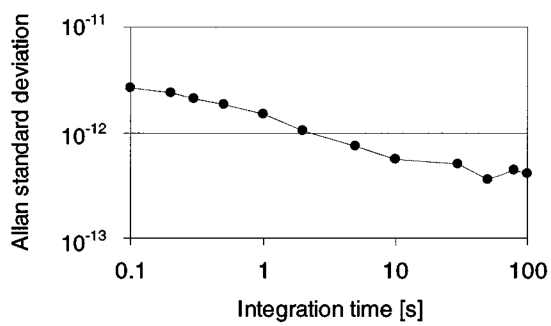


Fig. 9. Allan standard deviation of the laser frequency fluctuations as a function of the integration time.

quality of the Er–Yb laser source with respect to the diode laser, similar or even better long-term stability and accuracy should be achieved with a frequency-doubled Er–Yb laser locked to potassium sub-Doppler transitions.

VI. Conclusion

A novel single-frequency Er–Yb bulk microlaser at 1.54 μm was frequency doubled with high efficiency in a periodically poled lithium niobate waveguide crystal. Up to 17 μW of 770-nm radiation were obtained starting from $\sim$8 mW of fundamental power. This second harmonic radiation was successfully used to achieve high-resolution saturation spectroscopy of the ^{39}K D_2 line, allowing for clear identification of the four different transitions and of the crossover lines between the corresponding hyperfine sublevels. Frequency locking of the Er–Yb laser against the strongest crossover line provided for a relative frequency instability at the 10^{-12} level reaching a lowest value of 3.6×10^{-13} for an integration time of 70 s, as derived from the closed-loop error signal. This result is comparable to the best frequency stabilities attained in the 1.55-μm spectral region. It opens the way to the development of excellent frequency standards based on this compact frequency-doubled laser source and sub-Doppler atomic lines. The narrow linewidth of this solid-state laser is particularly attractive for locking to narrow, sub-megahertz transitions, e.g., to the Rb 5S $\rightarrow$ 5D two-photon transition near 778 nm [30].

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