Frequency stability at the kilohertz level of a rubidium-locked diode laser at 192.114 THz

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The frequency stability of a 1560-nm diode laser, whose second harmonic was locked to ^{87}Rb sub-Doppler lines, was characterized by measuring the beat frequency relative to a 780-nm reference laser that was locked to sub-Doppler lines of another rubidium cell. The square root of the Allan variance reached a minimum value of 7.5×10^{-12} in 1 s, which corresponded to frequency variations of 1.44 kHz for the 1560-nm laser. The frequency reproducibility of the system was $\approx 1 \times 10^{-9}$. These values are better than those that can be achieved by locking to Doppler-broadened transitions at the 1550-nm wavelength band. © 1998 Optical Society of America

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1. Introduction

Optical frequency standards near the 1550-nm transmission window of optical fibers are required for many applications: optical communication systems that employ wavelength division multiplexing,[1,2] optical frequency synthesizers,[3] optical wavemeters, as well as for high-resolution laser spectroscopy and metrology.[4] Numerous studies have been devoted to the absolute stabilization of 1550-nm lasers. Frequency stabilization was achieved, for example, by locking to molecular lines of NH_3,[5] C_2H_2,[6] HCN,[7] and HI,[8] as well as by locking to optogalvanic lines of noble gases[2,9] or to optically pumped Rb lines.[10] In most of these experiments, the locking was done to transitions whose linewidth was dominated by Doppler broadening—typically several hundred megahertz. Sub-Doppler lines of optically pumped Rb lines[10] or optogalvanic lines of noble gases[9] have been observed, with typical linewidths of several tens of megahertz. However, additional excitation is required to probe these lines, which may cause unwanted perturbations to the excited transition.[10] Improved stability and accuracy were obtained[11] recently by locking to narrow sub-Doppler lines of C_2H_2 and HCN. However, a Fabry–Perot enhancement cavity was employed to achieve sufficient power for saturation spectroscopy of these weak molecular lines.

Another method for frequency stabilization is second-harmonic generation and locking to sub-Doppler atomic lines at the second harmonic. Possible atomic transitions include the Rb D_2 line at 780 nm,[12,13] the K D_1 line at 770 nm,[14,15] and the Rb $5s \rightarrow 5d$ two-photon transition at 778 nm.[16,17] Second-harmonic power level in the microwatt range is sufficient for locking directly to sub-Doppler resonant lines. Other possibilities are to phase lock[16] or injection lock[17] the second-harmonic signal to a powerful laser at the second harmonic, which can be locked to a sub-Doppler transition. For realization of these possibilities, the required second-harmonic power level should also be in the microwatt range.[16,17] However, to achieve this power level is not trivial with the relatively low-power (typically a few milliwatts) sources near 1550 nm. Two methods have been used to date to reach the required power levels: resonant second-harmonic generation[13,16,17] and guided-wave quasi-phase-matched second-harmonic generation in a periodically poled $LiNbO_3$ waveguide.[12,15] The latter technique has several practical advantages in terms of smaller physical size and single-pass operation, which overcome the difficulties of maintaining frequency locking between the laser and resonant enhancement cavity. Single-pass doubling in a waveguide was recently used by us for

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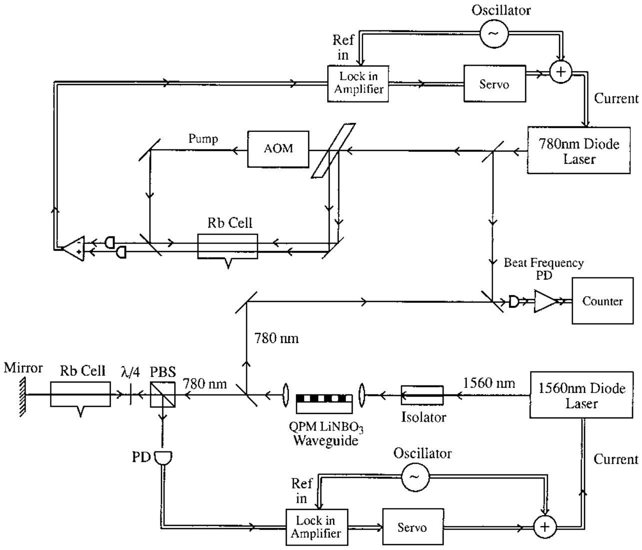

Fig. 1. Experimental setup for characterizing the frequency stability of the Rb-locked 1560-nm diode laser: AOM, acousto-optic modulator; PD, photodetector; PBS, polarizing beam splitter.

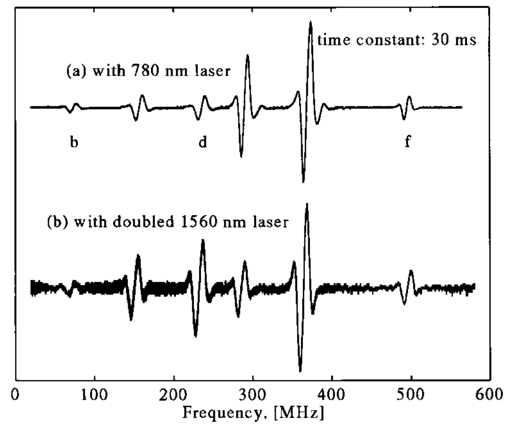

Fig. 2. Comparison between the sub-Doppler spectrum of ^{87}Rb $5S_{1/2}$ ($F'' = 2$) $\rightarrow 5P_{3/2}$ ($F' = 1, 2, 3$) transitions, labeled b, d, and f, respectively, obtained with the 780-nm diode laser and with the frequency-doubled 1560-nm laser. Both lasers were locked to the d/f crossover line.

locking to the Rb line[12] and the K line[15] and was also used earlier to double the 1319-nm Nd:YAG and lock the second harmonic to I_2 transitions.[18]

Even though the natural linewidth of atomic lines is less than 10 MHz, the Rb and K lines are considerably narrower frequency discriminators than the Doppler-broadened lines[2–8] and are also narrower than the excited-state atomic transitions[9,10] at 1550 nm. Hence, we expect to obtain improved stability and reproducibility. Until now,[12] only a single laser was used, hence the frequency tracking capability rather than the frequency stability could be evaluated by monitoring the error signal under locked operation. The error signal measurement is insensitive to systematic errors and cannot be used to evaluate the frequency reproducibility of the system. Here we report beat frequency measurements between two lasers, one of which, lased at 1560 nm, was frequency doubled and locked to Rb sub-Doppler lines and a reference system that was based on a 780-nm external cavity diode laser locked to Rb sub-Doppler lines of another absorption cell. The beat note measurements fully enabled us to characterize the frequency stability and reproducibility.

2. Experimental Setup

The setup for doubling the 1560-nm laser and locking to Rb was described in detail in Ref. 12 and was slightly improved since then (see Fig. 1). Our light source, a commercial external cavity diode laser (New Focus 6262) was passed through an optical isolator (75-dB reverse isolation) and coupled into a 3-cm-long periodically poled $LiNbO_3$ waveguide doubler. Ferroelectric domain inversion with a period of 14 μm was obtained by electric field poling, and the channel waveguide was fabricated by annealed proton exchange in a process described in detail in Ref. 19. The single-pass efficiency for SHG of 1560.5 nm in the waveguide was 120% W^{-1} at 33 °C. We coupled ~1 mW into the waveguide and obtained ~1.2 μW at 780.25 nm. The waveguide output face was polished at a 15-deg angle with respect to the waveguide to avoid etalon effects that cause wavelength-dependent output power fluctuations. The ratio of the minimum to maximum second-harmonic power generated as the wavelength was tuned was ~0.5 with perpendicular faces[12] and 0.96 with an angled face. Antireflection coatings could significantly reduce this effect.

The SHG beam was split by a 50/50 beam splitter: 0.6 μW was sent to the beat note detector and the remaining light was used for saturation spectroscopy in a 7.5-cm-long Rb cell. A quarter-wave plate and a polarizing beam splitter were used to direct the transmitted light into the cell and the reflected light onto the detector. The frequency was dithered using the laser current at a frequency of 1.8 kHz, and the third-harmonic component at 5.4 kHz was measured using a lock-in amplifier. The third-harmonic detection method was used because it nearly eliminates the contribution of the broad Doppler envelope while providing a suitable signal for locking to the narrow sub-Doppler lines. The laser frequency was locked to the crossover transition between the d ($F'' = 2 \rightarrow F' = 2$) and f ($F'' = 2 \rightarrow F' = 3$) lines of ^{87}Rb $5S_{1/2} \rightarrow 5P_{3/2}$ levels; see Fig. 2. The measured linewidth of this transition was ≈8 MHz. The absolute frequency of this line was measured recently with a precision of 1.4×10^{-11}.[20] Hence the second harmonic of a diode laser at a frequency of 192.114 THz, which is locked to the Rb line, can be set with a potential accuracy of 2.7 kHz. Frequency locking can be obtained either by applying a voltage to the piezoelectric transducer that rotates the feedback mirror inside the laser cavity or by adjusting the laser current. Both options were tested and better results were obtained using the laser current. The servo consisted of a proportional + integral amplifier and the open loop gain of this system as a function of frequency f in hertz was $\sim 700/f$.

Our reference system was based on a homemade external cavity diode laser. We used a 50-mW SDL-5401 diode laser in a Littrow configuration. The laser light was collimated and sent to a 1200-lines/mm ruled diffraction grating. The first-order diffracted beam was fed back into the laser diode, whereas the reflected beam from this grating was the light source for our experiment. Wavelength tuning was achieved by rotating the grating with a fine adjustment screw or, for finer tuning, with a piezoelectric transducer. Ultrafine wavelength tuning was achieved by altering the bias current. The diode laser was driven by a low noise current controller and its temperature was stabilized at the millikelvin level using a thermoelectric cooler and a proportional, integral, and differential temperature controller. The laser power was split into two probe beams and one counterpropagating pump beam that coincided with one of the probe beams. The pump beam was shifted by 42.8 MHz using an acousto-optic modulator. The pump power was $\approx 45\ \mu W$ and the power of each of the probe beams was $\approx 20\ \mu W$.

We tested two schemes for locking the laser to sub-Doppler lines. First we locked the laser to the side of the sub-Doppler line.[21] Subtracting the output of the two detectors that detected separately the two probe beams provided a sub-Doppler signal. The obtained linewidth, ~ 10 MHz, was slightly broader in this system, possibly because of gas contamination in this cell. This locking method does not require frequency modulation of the laser, but it is less reproducible than locking to line center. In the second scheme, the sub-Doppler line was observed by applying a small modulation frequency to the laser current and detecting the third-harmonic frequency of the modulation frequency, as was done with the 1560-nm laser system. The sub-Doppler signal was amplified and used to alter the laser bias current to keep its frequency on the hyperfine line center. Here we also used the difference between the two probe beams—one of which overlapped with the counterpropagating pump beam—to reduce systematic frequency offsets owing to the Doppler envelope and residual amplitude noise of the laser. Since only the pump beam of the 780-nm laser system was frequency shifted, the beat frequency between the two lasers when locked to the same transition was obtained near half of the acousto-optic modulation frequency of -21.4 MHz. This enabled us to eliminate residual amplitude noise, which was added at the modulation frequency by the acousto-optic modulator, by filtering the beat frequency signal using a radio frequency bandpass or low-pass filter.

3. Frequency Stability Measurements

The beat frequency between the two lasers was measured by a fast Si photodiode followed by a radio frequency amplifier and a SRS 620 frequency counter. The two lasers were modulated at the same frequency and phase and with the same modulation depth (≈ 10 MHz) to avoid modulation broadening of the beat note frequency. The square root of the Allan variance[22] of the beat frequency between the locked lasers is shown in Fig. 3. A similar measurement, while the 1560-nm laser was free running, is also shown for comparison. In this case the reference system was locked to the side of the d/f transition. As can be seen, the frequency stability was improved considerably. The best result of 7.5×10^{-12} in 1 s corresponded to frequency variations of 1.44 kHz for the 1560-nm laser. The stability slowly deteriorated at longer measurement times. However, all the measurements between 0.05 and 50 s were better than 3×10^{-11}. Similar results were also obtained when the reference laser was locked to the side of the d/f crossover lines (best result of 6.9×10^{-12} at 1 s), thus indicating that in both measurements the stability was limited by the 1560-nm laser system and not by the reference system. The higher values of the root Allan variance at the shorter time scale could be partly attributed to the modulation broadening of the beat note signal inasmuch as only the 1560-nm laser was frequency modulated[23] in these measurements. In addition, a less mechanically stable 780-nm external cavity laser design was used when the laser was locked to the side of the d/f line, whereas an improved and more stable design was used when the 780-nm laser was locked to line center.

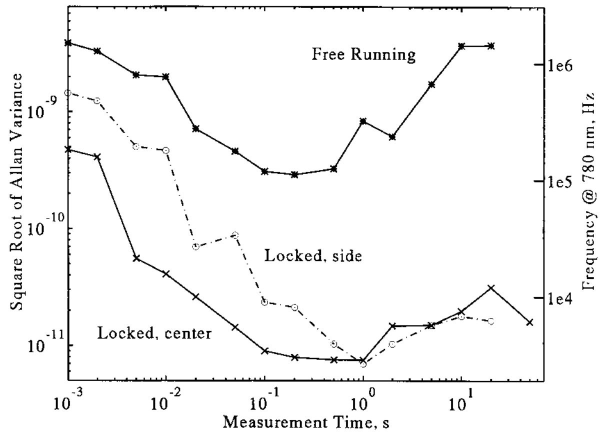

Fig. 3. Square root of the Allan variance between the doubled 1560-nm laser and the 780-nm reference laser. The 1560-nm was free running in one measurement and under lock in the other two measurements. The 780-nm laser was kept locked in all the measurements. In the measurement labeled center it was locked to the center of the Rb d/f transition and in the other two measurements it was locked to the side of this transition. The right axis scale refers to frequencies at 780 nm.

Figure 4 shows the time variation of the beat frequency when both lasers are locked to Rb line center. As can be seen, during the measurement period the locked lasers were kept within 120 kHz (at 780 nm). For comparison, we took another measurement in which the 1560-nm laser was free running. In this case the drift of the doubled 1560-nm laser frequency was ~ 16 MHz at 780 nm.

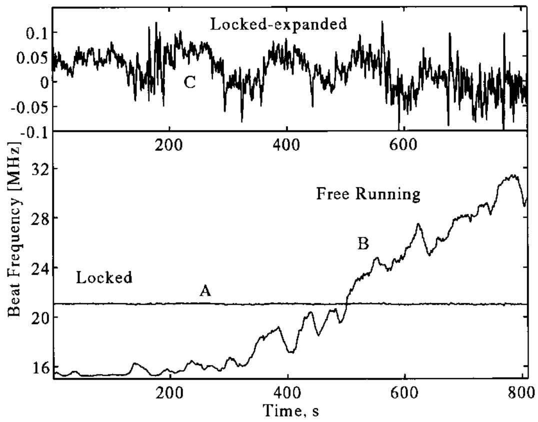

Fig. 4. Variation of the beat frequency (at 780 nm) between the two lasers: A, the 1560 nm was under lock; B, the 1560 nm was free running; C, expanded frequency scale of A. The 780-nm laser was kept locked in all the measurements.

To estimate the reproducibility we occasionally probed the beat frequency over a period of eight days. During this time the lasers were locked and unlocked at numerous times, and the beam alignment was also adjusted occasionally. If both lasers were locked exactly to line center and there were no systematic offsets, the beat frequency should have been exactly half of the acousto-optic modulation frequency of -21.4 MHz. In practice, the average beat frequency was 21.072 MHz. Various effects can cause systematic offset of the beat frequency, including parasitic interference owing to reflections from optical elements along the beam path, residual laser amplitude noise at the modulation frequency and its harmonics, background gas contamination in the Rb cells, and light-induced line shape modifications.[24] The peak-to-peak variation in the beat frequency was 655 kHz and the standard deviation was 228 kHz, both measured at 780 nm. We thus conclude that the reproducibility was better than 1×10^{-9}, which corresponded to $<$200 kHz at 1560 nm.

4. Summary and Conclusions

The frequency stability and reproducibility that we obtained are an order of magnitude better than typical results obtained by locking to Doppler-broadened lines at 1550 nm. Our results are slightly better at short measurement times than the best results obtained so far by locking to Doppler-broadened lines at this wavelength range[25] (square root of the Allan variance of $\leq 5 \times 10^{-11}$ by locking to C_2H_2 lines; reproducibility, 2 MHz), which were achieved by using external phase modulators. Better stability—of the order of 10^{-12}—was reached with sub-Doppler C_2H_2 lines,[11] but this method required an enhancement cavity, whereas in our system, standard and simple spectroscopic methods were used. Furthermore, in the system described here only a small fraction of the light is frequency doubled and used for stabilization, thus most of the laser power remains available for applications. In contrast, locking to sub-Doppler molecular lines near 1550 nm may require a significant fraction of the laser power, owing to their extremely high saturation intensity. It should also be noted that the absolute frequencies of molecular transitions near 1550 nm, e.g., HCN,[26] are known with a precision of 10^{-9}, which is approximately 2 orders of magnitude less accurate with respect to the Rb transitions.

The frequency stability and reproducibility can be further improved with higher pump power. Indeed, the Rb sub-Doppler spectra obtained with the frequency-doubled 1560-nm laser was much noisier than the one obtained with the more powerful 780-nm laser; see Fig. 2. Furthermore, the higher second-harmonic power can be used in configurations in which systematic frequency offsets are reduced, e.g., using a dual probe configuration as in the 780-nm laser system, which reduces systematic errors in the locking point owing to the Doppler envelope and the residual intensity noise of the laser. Frequency modulation spectroscopy using external modulators can further reduce the systematic offsets owing to residual intensity noise. As shown recently, by use of Ti:Al_2O_3 lasers,[20] it is possible for one to obtain stability of 2×10^{-13} and reproducibility of 1×10^{-11} by locking to Rb D_2 transitions at 780 nm.

Recent improvements in nonlinear materials and in the available power level of diode lasers at 1550 nm open new possibilities for development and improvements in second-harmonic-stabilized sources. Distributed feedback lasers emitting 50 mW are now commercially available. Similar power levels can also be obtained by amplifying a lower power source in an Er-doped fiber amplifier. As for guided-wave doublers, conversion efficiency of 250% W^{-1} has already been achieved.[19] Doubling a 50-mW source with this conversion efficiency should provide $\approx$6 mW at the second harmonic. This power level is 3 orders of magnitude higher than that achieved in this study and should lead to an improved frequency standard. Furthermore, this power level may be sufficient for direct detection and locking to the Rb $5s \rightarrow 5d$ two photon transition at 778 nm, without the need to phase lock or injection lock to another powerful laser at the second harmonic. Finally, since the doubling efficiency of a 1-cm-long bulk periodically poled $LiNbO_3$ is $\approx 1\ \%W^{-1}$ at 1550 nm under optimal focusing conditions[27] and assuming an effective nonlinear coefficient of 17 pm/V, power levels of several microwatts for locking directly to resonant lines of Rb and K can be generated without the use of a waveguide or a resonant enhancement cavity. This would greatly reduce the mechanical tolerances of the doubling system.

The advantages of locking to sub-Doppler resonant atomic lines at the second-harmonic frequency, rather than to Doppler-broadened lines, include improved frequency stability and reproducibility and smaller dither amplitude. In addition to industrial applications, the development of high-quality frequency standards at 1550 nm opens new possibilities for performing precision measurements in the wavelength band in which the photonics technology is the most developed.

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References

1. D. J. E. Knight, K. I. Pharaoh, G. P. Barwood, and D. A. Humphreys, "A review of user requirements for, and practical possibilities for, frequency standards for the optical fiber communication bands," in *Frequency Stabilized Lasers and Their Applications*, Y. C. Chung, ed. Proc. SPIE **1837,** 106–114 (1993).
2. Y. C. Chung, "Frequency-locked 1.3 and 1.5 μm semiconductor lasers for lightwave systems applications," J. Lightwave. Technol. **8,** 869–876 (1990).
3. O. Ishida and H. Toba, "Lightwave synthesizer with lock-in detected frequency references," J. Lightwave. Technol. **9,** 1344–1352 (1991).
4. H. Sasada and K. Yamada, "Calibration lines of HCN in the 1.5-μm region," Appl. Opt. **29,** 3535–3547 (1990).
5. T. Yanagawa, S. Saito, and Y. Yamamoto, "Frequency stabilization of 1.5-μm InGaAs distributed feedback laser to NH_3 absorption lines," Appl. Phys. Lett. **45,** 826–828 (1984).
6. Y. Sakai, S. Sudo, and T. Ikegami, "Frequency stabilization of laser diodes using 1.51–1.55 μm absorption lines of $^{12}C_2H_2$ and $^{13}C_2H_2$," IEEE J. Quantum Electron. **28,** 75–81 (1992).
7. S. Yoshitake, K. Akiyama, M. Iritani, and H. Murayama, "1.55-μm band practical frequency stabilized semiconductor laser using C_2H_2 or HCN absorption lines," in *Frequency Stabilized Lasers and Their Applications*, Y. C. Chung, ed., Proc. SPIE **1837,** 124–133 (1992).
8. F. Bertinetto, P. Gambini, R. Lano, and M. Puleo, "Stabilization of the emission frequency of 1.54 μm DFB laser diodes to Hydrogen Iodide," IEEE Photon. Technol. Lett. **4,** 472–474 (1993).
9. A. J. Lucero, Y. C. Chung, S. Reilly, and R. W. Tkach, "Saturation measurements of excited state transitions in noble gases using the optogalvanic effect," Opt. Lett. **16,** 849–851 (1991); U. H. P. Fischer and C. V. Helmolt, "Saturation and isotopic shift of the Kr 84 excited-state transition at 1547.825 nm," IEEE Photon. Technol. Lett. **7,** 65–67 (1995).
10. M. Breton, P. Tremblay, C. Julien, N. Cyr, M. Tetu, and C. Latrasse, "Optically-pumped rubidium as a frequency standard at 196 THz," IEEE Trans. Instrum. Meas. **44,** 162–165 (1995).
11. M. de Labachelerie, K. Nakagawa, Y. Awaji, and M. Ohtsu, "High frequency stability laser at 1.5 μm using Doppler-free molecular lines," Opt. Lett. **20,** 572–574 (1995).
12. V. Mahal, A. Arie, M. A. Arbore, and M. M. Fejer, "Quasi-phase-matched frequency doubling in a waveguide of a 1560-nm diode laser and locking to the rubidium D_2 absorption lines," Opt. Lett. **21,** 1217–1219 (1996).
13. M. Poulin, N. Cyr, C. Latrasse, and M. Tetu, "Progress in the realization of a frequency standard at 192.1 THz (1560.5 nm) using ^{87}Rb D_2 line and second harmonic generation," IEEE Trans. Instrum. Meas. **46,** 157–161 (1997).
14. W. Wang, A. M. Akulshin, and M. Ohtsu, "Pump-probe spectroscopy in potassium using an AlGaAs laser and the second harmonic generation of an InGaAsP laser for frequency stabilization and linking," IEEE Photon. Technol. Lett. **6,** 95–97 (1994).
15. A. Bruner, A. Arie, M. A. Arbore, and M. M. Fejer, "Frequency stabilization of a diode laser at 1540 nm by locking to sub-Doppler lines of potassium at 770 nm," Appl. Opt. **37,** 1049–1052 (1998).
16. M. Zhu and R. W. Standridge, Jr., "Optical frequency standard for optical fiber communication based on the Rb $5s \rightarrow 5d$ two-photon transition," Opt. Lett. **22,** 730–732 (1997).
17. M. Poulin, C. Latrasse, N. Cyr, and M. Tetu, "An absolute frequency reference at 192.6 THz (1556 nm) based on two-photon absorption line of rubidium at 778 nm for WDM communication systems," IEEE Photon. Technol. Lett. **9,** 1631–1633 (1997).
18. A. Arie, M. L. Bortz, M. M. Fejer, and R. L. Byer, "Iodine spectroscopy and absolute frequency stabilization with the second harmonic of the 1319-nm Nd:YAG laser," Opt. Lett. **18,** 1757–1759 (1993).
19. M. A. Arbore and M. M. Fejer, "Singly resonant optical parametric oscillation in periodically poled lithium niobate waveguides," Opt. Lett. **22,** 151–153 (1997).
20. J. Ye, S. Swartz, P. Jungner, and J. L. Hall, "Hyperfine structure and absolute frequency of the ^{87}Rb $5P_{3/2}$ state," Opt. Lett. **21,** 1280–1282 (1996).
21. A. Bruner, V. Mahal, I. Kiryuschev, A. Arie, M. A. Arbore, and M. M. Fejer, "Frequency stability at the kHz level of Rb-locked diode laser at 1560 nm," in *Conference on Lasers and Electro-Optics*, Vol. 11 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), paper CThL35, p. 378.
22. D. W. Allan, "Statistics of atomic frequency standards," Proc. IEEE **54,** 221–230 (1966).
23. J. Rutman, "Characterization of phase and frequency instabilities in precision frequency sources: fifteen years of progress," Proc. IEEE **66,** 1048–1074 (1978).
24. R. Grimm and J. Mlynek, "The effect of resonant light pressure in saturation spectroscopy," Appl. Phys. B **49,** 179–189 (1989).
25. F. Bertinetto, P. Gambini, R. Lano, and M. Puleo, "Frequency stabilization of DFB laser diodes to the P(3) line of acetylene at 1.52688 μm by external phase modulation," in *Frequency Stabilized Lasers and Their Applications*, Y. C. Chung, ed., Proc. SPIE **1837,** 154–163 (1992).
26. Y. Awaji, K. Nakagawa, M. de Labachelerie, M. Ohtsu, and H. Sasada, "Optical frequency measurement of the $H^{12}C^{14}N$ Lamb-dip-stabilized 1.5-μm diode laser," Opt. Lett. **20,** 2024–2026 (1995).
27. G. D. Boyd and D. A. Kleinman, "Parametric interaction of focused Gaussian light beams," J. Appl. Phys. **39,** 3597–3639 (1968).