Quasi-phase-matched frequency doubling in a waveguide of a 1560-nm diode laser and locking to the rubidium D_2 absorption lines

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An external-cavity 1560-nm diode laser was frequency doubled in a 3-cm-long periodically poled $LiNbO_3$ waveguide doubler with 120% W^{-1} conversion efficiency. The 780-nm light was used to detect the D_2 transitions of Rb, and the laser frequency was locked to Doppler-broadened lines of Rb. Furthermore, the ~1 μW of second-harmonic power was sufficient for detecting the sub-Doppler lines of Rb, and the laser was locked to a ^{87}Rb crossover line.

Lasers operating at fixed and known frequencies near the 1550-nm transmission window of optical fibers are required for densely packed multiwavelength communication systems.[1] Such lasers may also be required for coherent optical communication systems to ease the acquisition and locking of a local oscillator laser to a transmitter laser and for achieving cold-start communication.[2] In addition, absolutely stabilized sources may be applicable to fiber-optic sensors and as frequency standards for high-resolution spectroscopy. Optical frequency standards can be realized by locking to atomic or molecular transitions. Molecular absorptions in the 1550-nm wavelength range, e.g., ammonia,[3] acetylene,[4,5] and hydrogen iodide,[6] are usually weak overtone or combination bands. Lasers at 1550 nm were locked to Doppler-broadened transitions of these molecules.[4,6] However, locking to sub-Doppler transitions of these lines with the available low-power diode lasers at 1550 nm usually requires signal enhancement techniques.[5] Atomic transitions that can be used as frequency references, e.g., transitions between excited states in noble gases (Ar, Kr, etc.)[2] and transitions between upper levels in Rb,[7] do not originate from the ground state. Hence additional excitation, electrical (with a discharge lamp[2]) or optical (with another laser[7]), is required for populating one of these upper levels.

An alternative approach that may overcome the difficulties associated with frequency references near 1550 nm is second-harmonic generation (SHG) and locking to absorption lines near 780 nm. A thoroughly characterized reference at 780.25 nm is the atomic-Rb D_2 line.[8] This reference was already used to stabilize 1560-nm laser diodes with the internally generated second harmonic of diode lasers,[9] but the SHG power was only 2 pW. Recently bulk external SHG in $KNbO_3$ crystal with a second-harmonic power of 2.2 nW was employed for the same goal.[10] Locking to a Doppler-broadened line was possible, but the power level was not sufficient to saturate the absorption for locking to sub-Doppler lines. Frequency doubling in $KNbO_3$ was also used to lock to K at 770 nm,[11] with a second-harmonic power of 20 nW.

Because the power levels of diode lasers near 1550 nm are quite low (typically a few milliwatts), higher-efficiency frequency conversion is required for detection and locking to sub-Doppler lines as well as to improve the signal-to-noise ratio for locking to Doppler-broadened lines. A technique that may achieve this goal is quasi-phase-matched[12] (QPM) frequency conversion in a waveguide. In QPM doubling, a periodic modulation of the material nonlinear coefficient compensates for the phase velocity mismatch between the fundamental and the second-harmonic waves. This technique permits the use of large nonlinear coefficients, e.g., d_{33}, in $LiNbO_3$ that are not accessible by birefringent phase matching. In $LiNbO_3$ the improvement in conversion efficiency compared with birefringent phase matching is $(2d_{33}/\pi d_{31})^2 \sim 20$, where $2/\pi$ is the QPM reduction factor and d_{31} is the effective nonlinear coefficient for birefringent phase matching. Further improvement in conversion efficiency is obtained by waveguide confinement. Furthermore, room-temperature operation, as well as relaxed temperature and wavelength tolerances, is possible. The use of QPM waveguides for optical frequency standards at the 1300-nm fiber-optic transmission window has already been demonstrated[13]: the second harmonic of a 1319-nm Nd:YAG laser was locked to I_2 transitions near 660 nm.

We applied the technique of waveguide QPM frequency conversion for efficient single-pass doubling of a 1560-nm external-cavity diode laser. The second-harmonic power was sufficiently high that we could detect sub-Doppler lines, and the laser was locked to Doppler-broadened lines as well as to sub-Doppler lines of Rb near 780 nm. The experimental setup for locking to Doppler-broadened lines of Rb is shown in Fig. 1(a). We used an external-cavity diode laser, New Focus 6262, with a tuning range of 1491–1568 nm. According to the manufacturer's specifications the laser linewidth is <300 kHz in 50 ms

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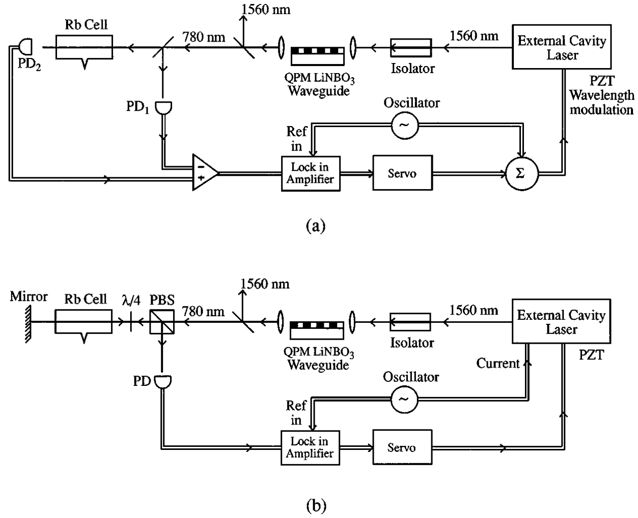

Fig. 1. Experimental setups for locking the external cavity laser to Rb lines. (a) Doppler-broadened lines: PD_1, PD_2, photodetectors. (b) Sub-Doppler lines: PD, photodetector; PBS, polarizing beam splitter.

and <5 MHz in 5 s. The laser output was injected into a periodically poled $LiNbO_3$ waveguide doubler. To couple light into and out of the waveguide we used microscope objectives with a focal length of 4.5 mm and a numerical aperture of 0.55.

The channel waveguide device used was 3 cm long and single mode at the 1560-nm input wavelength, with mode size of 4 μm × 3 μm. The periodically poled substrate, with the period of 14 μm, was fabricated by electric field poling[14] of a patterned 0.5-mm-thick Z-cut wafer of congruent $LiNbO_3$. We designed the waveguide by using the linear and nonlinear properties of annealed proton exchanged $LiNbO_3$.[15] The waveguide sample was proton exchanged at 178 °C for 2.5 h to a depth of 0.55 μm through a lithographically defined mask of sputtered SiO_2 with 5.5-μm-wide channel openings. The sample was then annealed in air at 340 °C for 8.25 h. The single-pass efficiency for SHG of 1560.5 nm in the waveguide was 120% W^{-1} at 33 °C, with a FWHM bandwidth of 0.5 nm, indicating waveguide uniformity over 2.5 cm. The peak SHG efficiency could be tuned with temperature at a rate of ~0.06 nm/K. With an incident power of 2.3 mW at 1560.5 nm at the waveguide input and a coupling efficiency through the (uncoated) waveguide of 40%, we obtained 1 μW of power at 780.25 nm. This power level was 6 orders of magnitude greater than the level achieved by the laser's internal SHG[9] and 2–3 orders of magnitude greater than the level achieved by bulk SHG.[10,11]

The second-harmonic light passed through a 7.5-cm Rb cell. Owing to the formation of a parasitic étalon caused by the Fresnel reflections from the uncoated input and output faces of the waveguide, the power level coming out of the waveguide changed periodically while we scanned the wavelength. To overcome this effect we probed the 780-nm power before it entered the cell. The transmitted and reference power levels are shown in curve (a) of Fig. 2. We obtained the normalized cell transmission, curve (b), by dividing the transmission signal by the reference signal. The four Rb lines observed were between levels $5S_{1/2}$ and $5P_{3/2}$. Both isotopes, ^{85}Rb and ^{87}Rb, are present in the cell. Lines 87B and 87A in curve (b) of Fig. 2 correspond to ^{87}Rb transitions $F = 2 \rightarrow F = 1, 2, 3$ and $F = 1 \rightarrow F = 0, 1, 2$, respectively. Lines 85B and 85A correspond to ^{85}Rb transitions $F = 3 \rightarrow F = 2, 3, 4$ and $F = 2 \rightarrow F = 1, 2, 3$, respectively.

An error signal for locking to the center of the Doppler-broadened lines was obtained by wavelength modulation spectroscopy. The laser frequency was dithered with a piezoelectric actuator at a frequency of 1.8 kHz and modulation depth of ~600 MHz (at 1560 nm). This piezoelectric transducer changed the angle of a wavelength-tuning mirror inside the external-cavity laser. The difference between photodetectors PD_1 and PD_2 was measured with a lock-in amplifier at the modulation frequency. This signal, shown in curve (c) of Fig. 2, was used for stabilizing the

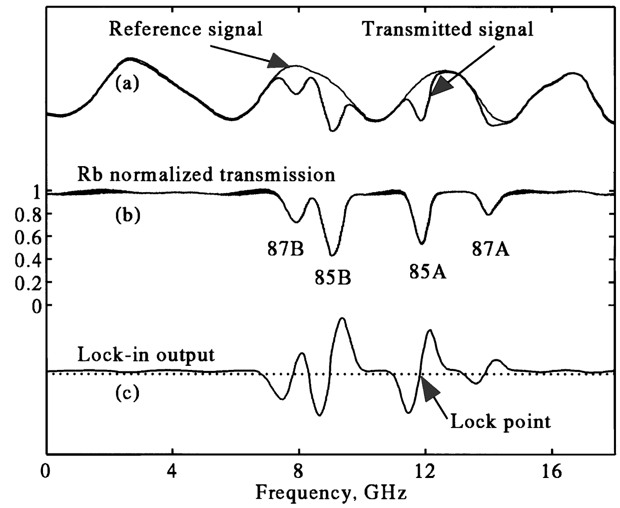

Fig. 2. (a) Measured power level of PD_1 (upper) and PD_2 (lower) as the laser is scanned through the Rb lines. (b) Normalized Rb cell transmission. (c) Error signal for locking to Doppler-broadened lines. Lock-in time constant, 1 ms.

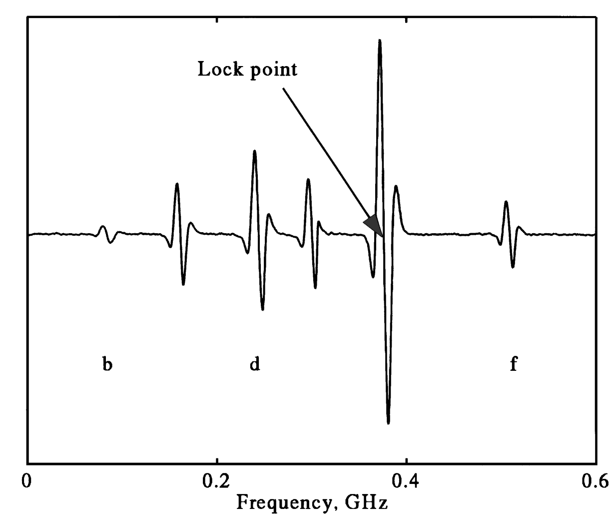

Fig. 3. Sub-Doppler spectrum of line 87B. Lock-in time constant, 100 ms.

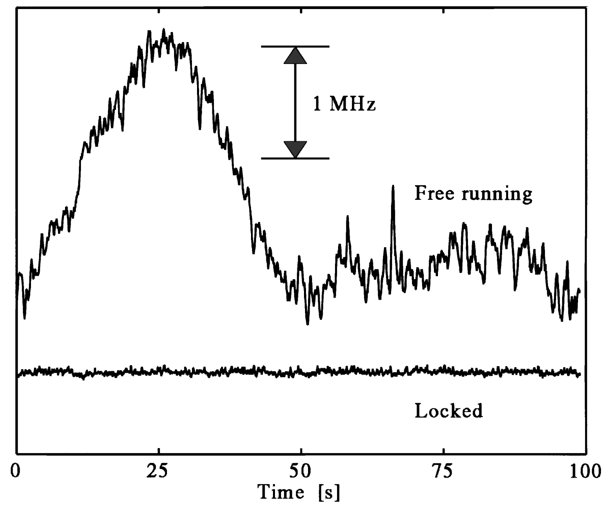

Fig. 4. Error signal of the laser frequency while the laser is free funning and while it is locked.

laser frequency by feeding it through a servo amplifier and a summing amplifier back to the laser.

Improved frequency accuracy and reproducibility require narrower frequency discriminators. The main broadening mechanism in the measurements of Fig. 2 was Doppler broadening, which was ~500 MHz at room temperature. For locking to sub-Doppler lines we used the setup shown in Fig. 1(b): the SHG light passed twice, back and forth, through the cell. A quarter-wave plate and a polarizing beam splitter were used to direct the forward light into the cell and the reflected light into the detector. A reference detector was not required in this case because the entire scanning range was much smaller than the free spectral range of the parasitic waveguide étalon. The beam diameter inside the cell was ~0.6 mm; hence the intensity was ~0.35 mW/cm^2. The frequency was dithered in this case by the laser current at a frequency of 1.6 kHz, and the third-harmonic component at 4.8 kHz was measured with a lock-in amplifier. The sub-Doppler spectrum of line 87B is shown in Fig. 3. The three transitions (labeled b, d, and f and corresponding to transitions $F = 2 \rightarrow F = 1, 2, 3$, respectively, in ^{87}Rb) and three crossover lines were clearly resolved. The linewidth was ~8 MHz. In a similar manner we obtained the sub-Doppler spectra of all the Rb lines near 780 nm.

The best signal-to-noise ratio was obtained for the d/f crossover line. Furthermore, the frequency of this line was measured with an accuracy of 1.5×10^{-10}.[8] We locked the laser to the d/f crossover line by feeding the output of the lock-in amplifier through a servo controller back to the laser piezoelectric actuator (PZT, Fig. 1). The error signal of the laser under lock, as well as while it was free running, is shown in Fig. 4. The improvement in the laser frequency stability under lock is clearly seen, and the trace indicates submegahertz frequency stability. The peak-to-peak excursion of the locked laser was only 148 kHz (at 1560 nm). We note that this estimate of the frequency stability does not take into account frequency shifts induced by the frequency discriminator itself. We intend to construct a frequency reference, using a Rb-locked diode laser at 780 nm, to carry a complete characterization of the frequency stability. We also plan to reduce the power fluctuations that are due to the étalon effect by polishing the output face of the waveguide to a nonperpendicular angle with respect to the waveguide. We will also extend the use of waveguide frequency conversion to nearby wavelengths by doubling a semiconductor laser at 1556 nm and locking to the Rb two-photon transition at 778 nm. The absolute frequency of this line was recently measured with an accuracy of 1.3×10^{-11}, and the systematic shifts are smaller than those of the D_2 line.[16]

In summary, we have demonstrated that quasi-phase-matched doubling in a waveguide of low-power 1550-nm diode lasers generates sufficient second-harmonic power for saturation spectroscopy. Locking to narrow sub-Doppler atomic lines should be useful for advanced frequency standards for 1550-nm wavelength division multiplexed optical communication.

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