Frequency stabilization of a frequency-doubled 1556-nm source to the $5S_{1/2} \rightarrow 5D_{5/2}$ two-photon transitions of rubidium

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Improvements in the power level of sources near 1550 nm and in the efficiency of waveguide frequency doublers enabled us to lock a frequency-doubled source directly to the $5S_{1/2} \rightarrow 5D_{5/2}$ two-photon transitions near 778 nm. We obtained a sufficiently powerful second-harmonic signal, exceeding 2 mW, by doubling an external-cavity diode laser that was amplified by an erbium-doped fiber amplifier in a periodically poled $LiNbO_3$ channel waveguide. Our experimental scheme can be used for realizing compact, high-performance frequency standards near 1550 nm for fiber-optic communication and sensing applications. © 2000 Optical Society of America

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Frequency-stabilized sources near 1550 nm are required for frequency references in dense wavelength-division-multiplexed optical communications systems,[1] fiber-optic strain sensing,[2] and precision measurement instruments such as wavemeters, frequency synthesizers,[3] and eye-safe distance meters. Locking to narrow sub-Doppler lines is required for greater frequency stability, accuracy, and reproducibility. However, at the fundamental wavelength this locking is a rather difficult task, owing to the high saturation intensity of molecular transitions.[4] Furthermore, atomic absorbers in this wavelength range require additional excitation, a process that can introduce unwanted frequency shifts. Another possibility for achieving locking is to use sub-Doppler atomic transitions at the second harmonic as frequency references. Second-harmonic powers as low as 1 μW are sufficient for saturation spectroscopy of resonant atomic lines, e.g., the Rb D_2 line at 780 nm (Ref. 5) or the potassium D_1 line at 770 nm.[6,7] Greater stability and accuracy are provided by the Rb two-photon transition near 778 nm, since its frequency is relatively insensitive to the laser beam's size and intensity.[8] Furthermore, the natural linewidth of the two-photon transition is considerably narrower than that of the Rb D_2 line.[9] The Rb lines near 778 nm have been measured by use of a frequency chain with an uncertainty of 2 kHz. However, detection of these lines requires much higher second-harmonic power, typically in the milliwatt range. Until now, the generated second-harmonic beam was not powerful enough, and hence another laser was required at 778 nm, and the two lasers were either phase locked[10] or injection locked.[11] As a result, those systems were neither compact nor simple. Recent improvements in the power level of sources and in the efficiencies of frequency doublers permit single-pass generation of much higher second-harmonic power levels. Hence, direct frequency locking with a single laser is now possible and is demonstrated in this Letter.

The experimental setup is shown in Fig. 1. The light beam from a commercial external-cavity diode laser (New Focus 6328-H) was passed through an optical isolator (75-dB reverse isolation) and coupled into an erbium-doped fiber amplifier (IRE-POLUS EAM-40) with a nominal saturation power of 16 dBm. A fiber polarization controller was used to obtain linear polarization at the fiber output that was parallel to the frequency-doubler extraordinary direction.[12] The beam size was adjusted by use of an optical telescope, for optimal coupling into a 4-cm-long periodically poled lithium niobate (PPLN) waveguide frequency doubler.[12]

We fabricated the waveguide by annealed proton exchange in PPLN. The device had a poling period of 14.5 μm, a waveguide width of 6.5 μm, and a proton-exchange depth of 0.7 μm. It was annealed for 26 h at 325 °C. We polished the waveguide output face at

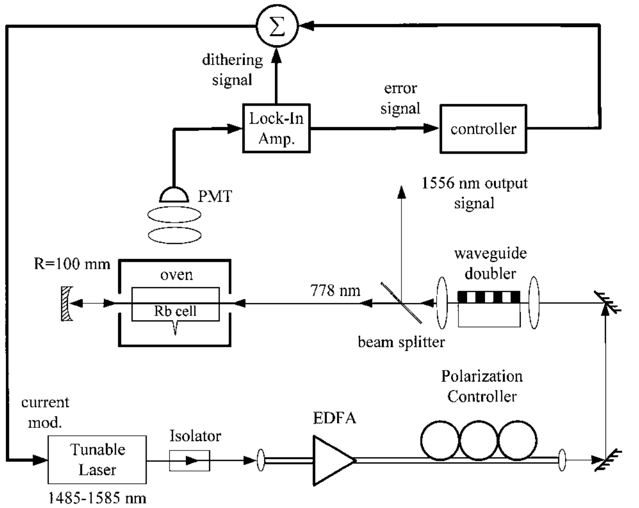

Fig. 1. Experimental setup for locking the laser to Rb two-photon transition: EDFA, erbium-doped fiber amplifier; PMT, photomultiplier tube.

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a 15° angle with respect to the waveguide axis to avoid parasitic etalon effects.[5] The doubler was held inside a temperature-controlled mount. We purposely designed the operating temperature for phase matching 1556.2 nm to be above room temperature (87 °C in our case) to avoid photorefractive damage. The waveguide confinement leads to doubling efficiencies that are 2 to 3 orders of magnitude higher than those of bulk frequency doublers. Figure 2 shows the wavelength dependence of the second-harmonic power.

The external efficiency of the waveguide was ~120% W^{-1}; see the inset of Fig. 2. Taking into account the Fresnel losses (14% and 20%, respectively, at the uncoated input and output faces of the waveguide) and the coupling efficiency (~57%), the single-pass internal doubling efficiency was ~610% W^{-1}. For an input power of ~39 mW the second-harmonic power was ~1.8 mW. Owing to an increase of more than an order of magnitude in the fundamental power and a nearly sixfold increase in the waveguide-doubling efficiency, this power level was ~3 orders of magnitude higher than that achieved in previous studies with PPLN waveguide doublers.[5,6] Furthermore, the second-harmonic power obtained in a single-pass scheme is at least 2 orders of magnitude greater than that achieved in previous studies with a bulk $KNbO_3$ crystal placed in a buildup cavity.[10,11] The second-harmonic signal is powerful enough for direct observation and locking to the Rb two-photon transition and saves us from dealing with the complexity of injection locking or phase locking another laser at 778 nm.

The waveguide output beam was separated by a dichroic beam splitter, and the second-harmonic beam was focused into a 75-mm-long Rb cell containing an enriched ^{87}Rb isotope. The Pyrex absorption cell was placed in an oven, and the typical operating temperature was 100 °C. The power of the second-harmonic beam entering the absorption cell was ~1.5 mW, and the beam shape was nearly circular, with a radius of ~0.2 mm. The transmitted beam was reflected back to the cell by a spherical mirror. The fluorescence at 420 nm was collected with two plano–convex lenses (focal length, 38.1 mm) and detected with a photomultiplier tube (Hamamatsu H5784). The typical fluorescence power that reached the detector was ~4 pW. The dominant noise in our system was caused by scattered light from the laser beam. This noise could be reduced by an interference filter whose transmission is centered at 420 nm.

Curve (a) of Fig. 3 shows the fluorescence spectrum of lines $5S_{1/2}$, $F_g = 2 \rightarrow 5D_{5/2}$, $F_e = 4, 3, 2, 1$ in ^{87}Rb. The laser wavelength was swept by ramping the bias current. The second-harmonic beam was chopped at a frequency of 1.5 kHz, and the photomultiplier tube output signal was demodulated by a lock-in amplifier. The measured linewidth of the $F_g = 2 \rightarrow F_e = 4$ transition was ~3.6 MHz. The natural linewidth of this transition is ~300 kHz.[9] Whereas part of the transition broadening is due to magnetic fields and transit time, the measurement resolution was limited mainly by the 1556-nm laser. The specified linewidth of our laser at measurements times similar to those required for scanning of a Rb transition is ~1 MHz at 1556 nm. The linewidth of the second-harmonic beam was two to four times wider, depending on whether the laser frequency noise was dominated by flicker noise or white noise.

Locking the laser frequency to a Rb transition usually requires a derivative signal. We obtained this signal by dithering the laser frequency, using current modulation at a rate of 5 kHz and demodulating the signal with a lock-in amplifier; see curve (b) of Fig. 3. The derivative signal was fed through a servo amplifier back to the laser current input. The chirp coefficient of the laser was ~36.8 MHz/mA. Slight variations (<1 mA) in the bias current were usually sufficient to keep the laser locked to the center of the Rb transition while having a negligible effect on the laser power. The open-loop gain of the entire control system as a function of frequency f [in Hz] is $\sim 7/f$. We also tested the system with higher open-loop gain. Although better suppression of noise was achieved, the locking could not be maintained for a long period of time, owing to the relatively low signal-to-noise ratio. A 25-min time trace of the error signal

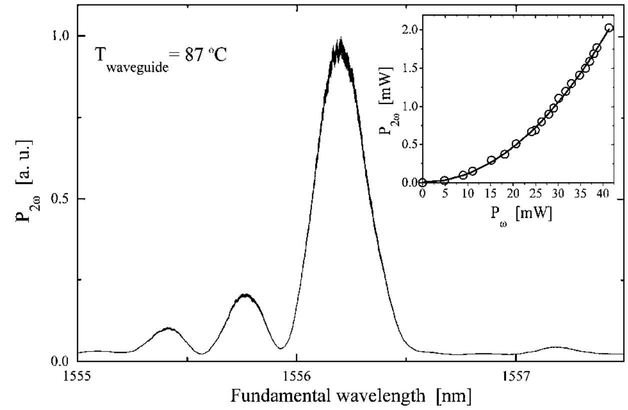

Fig. 2. Second-harmonic power as a function of fundamental wavelength. Inset, second-harmonic power as a function of the square of the input pump power. Solid curve, theoretical fit.

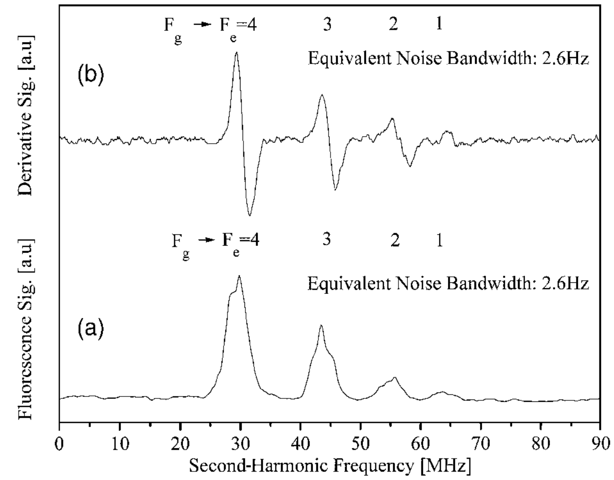

Fig. 3. (a) Fluorescence signal and (b) derivative signal of ^{87}Rb transitions near 778 nm.

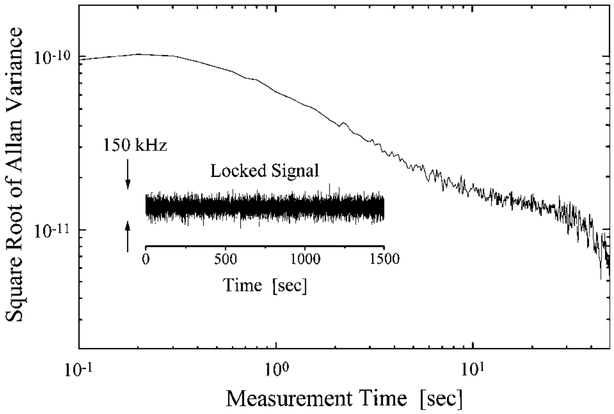

Fig. 4. Square root of Allan variance as a function of measurement time. Inset, time trace of the error signal while the laser is locked.

when the laser was locked is shown in the inset of Fig. 4, with a 100-ms integration time per measurement unit. We converted the time trace from voltage to frequency units by dividing it by the discriminator slope shown in curve (b) of Fig. 3. The long-term drift of the laser frequency at a typical rate of several megahertz per minute[5] is eliminated. The frequency fluctuations of the locked laser are below 150 kHz. We used a series of measurements with different integration times to calculate the square root of the Allan variance, as shown in Fig. 4. The stability for measurement times longer than 20 s is $\sim 1 \times 10^{-11}$, which corresponds to frequency variations of 1.9 kHz at 1556 nm. It should be emphasized that the Allan variance was derived from the error signal. This measurement is relatively insensitive to frequency variations introduced by the discriminator and therefore represents a lower limit of the frequency stability.

In conclusion, we have shown that efficient single-pass second-harmonic generation of a 1556-nm source with a PPLN waveguide doubler provides sufficient power for direct detection and locking to the Rb $5S_{1/2} \rightarrow 5D_{5/2}$ two-photon transition. Higher pump power provided by amplifiers with higher saturation power could lead to a substantial improvement in the two-photon transition signal, since the signal scales as the fourth power of the pump power. Improved spectral resolution can be achieved by use of a narrower-linewidth source, e.g., an Er–Yb solid-state laser[13] or a diode laser stabilized to an external cavity. It is encouraging to note that the linewidth measured with the existing system is already half of the natural linewidth of the Rb D_2 line.[5] The compact and simple experimental scheme eliminated the need for enhancement cavities or for another pump laser at the second harmonic. Thus this scheme enables one to realize high-performance portable frequency standards in the 1550-nm range.

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