Frequency-stabilized 1520-nm diode laser with rubidium $5S_{1/2} \rightarrow 7S_{1/2}$ two-photon absorption

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A 760-nm light source of >10 mW is obtained from a frequency-doubled external-cavity diode laser by use of using an erbium-doped fiber amplifier and a periodically poled lithium niobate waveguide. The $5S_{1/2} \rightarrow 7S_{1/2}$ two-photon transitions of rubidium are observed with such a light source. This laser frequency is locked to the Rb two-photon transitions with an instability of 10 kHz (1 s). Our experimental scheme provides a compact, high-performance frequency, standard in the S band (1480–1530 nm) for fiber-optic communication and sensing applications. © 2004 Optical Society of America

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Optical frequency standards and references are important for fundamental research, such as in setting definitions of physical constants, metrology, precision measurement, and industrial applications. Inasmuch as the importance of 1550-nm sources has grown over the past two decades as a result of their rising popularity in the telecommunication market, control and characterization of these sources have been intensively studied. Optical references in the S-band window (1480–1530 nm) can be utilized in dense wavelength-division multiplexing systems and components. In the applications of optical communications systems, atomic or molecular absorption provides wavelength references that are essential for the calibration of channel allocation in dense wavelength-division-multiplexed systems and related instrumentation.[1]

High stability, accuracy, and reproducibility of the frequency of light can be obtained by active locking to narrow sub-Doppler reference lines. In the infrared, the established frequency references are the weak molecular transitions of C_2H_2, which has high saturation intensity. Therefore, locking the laser frequency by using the Doppler-free saturation spectroscopy of C_2H_2 is a rather difficult task. This technique often requires a resonant cavity for enhancing the laser power.[2] Another approach is to utilize Doppler-free atomic transitions at the frequency of the second harmonic (SH) of the laser as frequency references.[3]

Frequency standards in various frequency regions, from rf to visible, have been built with atomic rubidium as an absorber. The 1 μW power of the SH generated from a 1560-nm laser source is sufficient for performing the saturation spectroscopy of resonant atomic lines, such as Rb D_2 at 780 nm.[3] Greater stability and accuracy are provided by the Rb two-photon transition, as its frequency is relatively insensitive to the laser beam's size and intensity. Furthermore, the natural linewidth of the two-photon transition is considerably narrower than that of the Rb D_2 line, but it requires much higher optical power, usually several milliwatts. The optical radiation of the Rb two-photon transition ($5S$–$5D$) at 778 nm has been recommended by the Committee International des Polds et Mésures as the standard for the meter.[4] In the $5S$–$5D$ transitions, because of the difference of the Landé G factors between S and D states, the magnetic field must be carefully shielded to prevent any shift of transition lines by the Zeeman effect.[5,6] The $5S$–$7S$ transitions are free from such Zeeman shifts[7] because both the lower and the upper levels have the same Landé g factors and therefore do not require magnetic shielding. This property makes a system less sensitive to the environment and is particularly useful in experiments on two-photon

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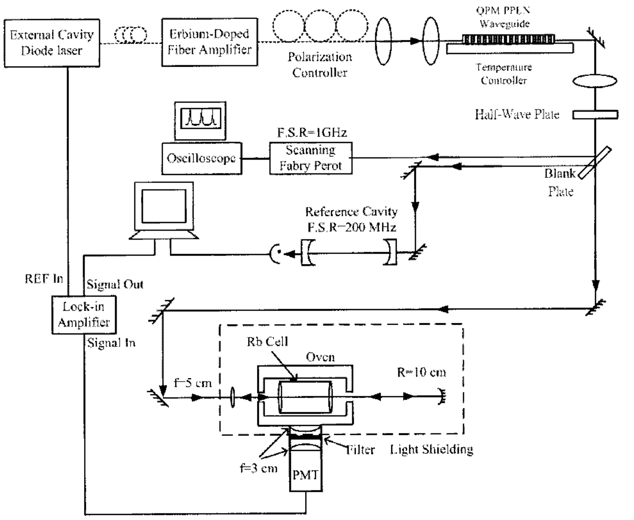

Fig. 1. Experimental setup for Rb $5S_{1/2}$–$7S_{1/2}$ two-photon spectroscopy: REF, reference signal; QPM, quasi-phase-matched; other abbreviations defined in text.

transitions in cold atom clouds that use magneto-optical traps.[8] The $5S$–$7S$ transitions are capable of providing a standard with a submegahertz accuracy for frequency-doubled 1520-nm light sources, which are located in the upper frequency end of the optical communication band. Together with the $5S$–$5D$ transitions (1556 nm/2) that are in the lower-frequency end,[3] one Rb two-photon spectrometer can provide accurate two-point calibration to cover the entire communication band.

Because the signal strength of the Rb $5S$–$7S$ transition is only 1% of that of the Rb $5S$–$5D$ transition, the laser power is most critical. The signal of the two-photon transitions is proportional to the squared SH laser power. As the SH power is proportional to the squared pump laser power, the two-photon transition signal scales as the fourth power of the pump laser power. Therefore we employed an erbium-doped fiber amplifier for amplification of the fundamental laser and a high-efficiency periodically poled lithium niobate (PPLN) waveguide for the SH generation. The high performance of the PPLN waveguide allowed more than 10 mW of SH power to be obtained with 95 mW of pump power. That is more than 10% conversion efficiency without any enhancement cavity. This SH power is enough to lock the laser frequency to the Rb $5S$–$7S$ transition in our experiment. Hence, without a slave laser and offset lock complications,[1] direct frequency locking with a single-laser system is demonstrated.

The experimental setup is shown in Fig. 1. The laser source is a commercial extended-cavity diode laser (Anritsu MG9638A) with 6-mW output power from 1500 to 1580 nm and a scan range of 1.2 GHz. The laser beam from the extended-cavity diode laser was amplified to 95 mW by an erbium-doped fiber amplifier (Technology Thesaurus Company). A fiber polarization controller rotated the laser polarization direction at the fiber output to be parallel to the extraordinary direction of the PPLN waveguide. The beam size was adjusted by use of an optical telescope for optimal coupling into a 52-mm-long PPLN waveguide. A small portion of laser beam was picked up by a blank glass plate and sent to a scanning Fabry–Perot interferometer for laser scanning diagnosis and a frequency-calibration reference cavity with a free spectral range (F.S.R) of 200.0 MHz. The absolute frequency of the laser was measured by a wavemeter with gigahertz accuracy.

The PPLN waveguides used in the experiment were 52 mm long with 46-mm poling regions and 1.5-mm-long mode filter and tapers on each side. The poling period was 15 μm, with a duty cycle of 50 ± 5%. The reverse proton exchange method was used for fabrication.[9] The periodically poled chip was proton exchanged in benzoic acid at 160 °C for 23.8 to a depth of 1.22 μm, annealed in air at 312 °C for 19.9 h, reverse proton exchanged in a melt of lithium nitrate, sodium nitrate, and potassium nitrate at 301 °C for 21.7 h. The typical internal SH generation conversion efficiency of the waveguides was in the range 90–100% W/cm^2, with propagation losses of 0.27–0.4 dB/cm. Noncritical phase matching was obtained for a waveguide width of 6.5 μm. The phase-matching wavelength at room temperature was 1508.7 nm. Mode filter widths ranging from 3 to 6 μm were used to allow for flexibility in mode matching on the input and output of the waveguides.

A Rb cell with a length of 25 mm was contained in an aluminum box and heated by two thin heating sheets. The finger of the cell protruded out of the container through an opening hole to keep the temperature 20–30 °C lower than in the rest of the cell. The typical temperature of the cell finger in this study was 110 °C, corresponding to a vapor pressure of 70 mPa and a number density of 5×10^{21} atoms/m^3. The 420 nm fluorescence was firstly collimated with a lens with focal length f = 30 mm and then passed through a 420-nm bandpass dielectric filter (CVI, manufacturer) to reduce the background noise caused by the scattered laser light. The fluorescence was measured with a photomultiplier (PMT; Hamamatsu R212, Fig. 1) with a 20-MΩ load resistor and a lock-in amplifier. A PC with an analog-to-digital converter card simultaneously recorded the two-photon signal and the fringes of the reference cavity. A light shield covered the entire apparatus to prevent any disturbance from room light. The 10-mW laser beam was focused to a beam size of 50 μm in the middle of the cell by an antireflection-coated lens with f = 50 mm. The transmitted beam was reflected back to the cell by a highly reflective spherical mirror with a radius of curvature of 100 mm.

The spectrum of the two-photon absorption is shown in Fig. 2. The laser intensity was chopped by the built-in amplitude modulation ($f_{\mathrm{mod}} = 20$ kHz) of the tunable laser. The measured linewidth was ~2.6 MHz at 760.1 nm, which is larger than the natural linewidth. In our experiment the broaden-

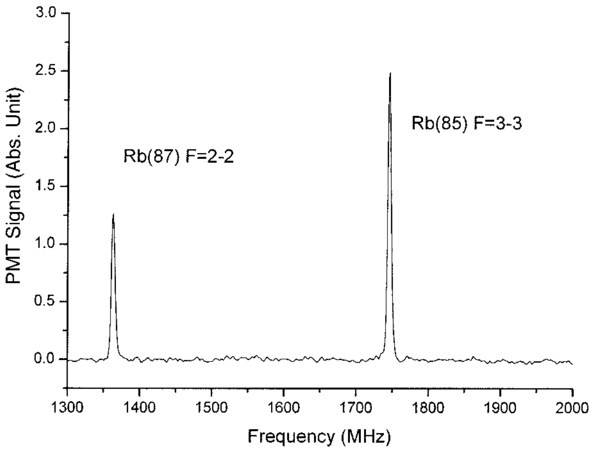

Fig. 2. Spectrum with the two transitions Rb (87) $F = 2$–2 and Rb (85) ($F = 3$–3). Its linewidth is 2.6 MHz at 760.1 nm.

ing of lines is dominated by the laser linewidth, which was measured to be ~1 MHz. The residual 0.6 MHz is due to transit-time broadening.

Using frequency modulation of the tunable laser to perform frequency-modulation spectroscopy, we then obtained the derivativelike line shape that is necessary for stabilization of the laser on the atomic transition. Figure 3 demonstrates a derivativelike line shape obtained by the frequency-modulation technique. The width of the signal (peak to peak) is 5.1 MHz at 760.1 nm, with a modulation depth 3 MHz and a modulation frequency of 40 kHz. The signal-to-noise ratio is ~30. To stabilize the laser frequency on the Rb transition, we fed the derivative signals through proportional-integral servo loops, and error signals were generated. A time trace of the error signal when the laser was locked is shown in Fig. 3. Using the lock error signal while the laser was locked, we estimated the frequency jitter to be 76 kHz. We also used a series of measurements with different measurement times to calculate the square root of the Allan variance, as shown in Fig. 4. With a measurement time of 10 s, the stability was better than 1×10^{-11}, which corresponds to a frequency variation of 2 kHz at 1520.2 nm.

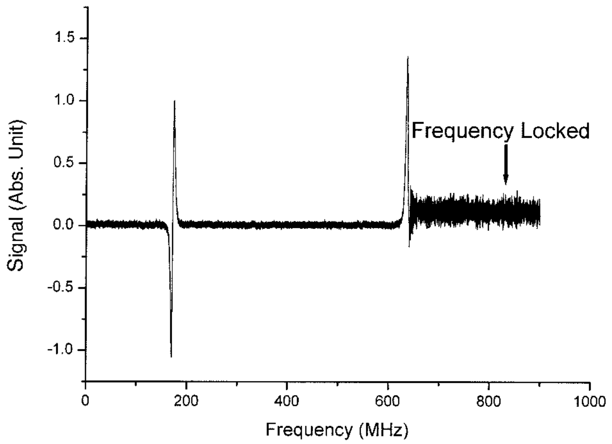

Fig. 3. Derivativelike line shape from the frequency-modulation technique. The signal-to-noise ratio is 30. A laser frequency is locked to the Rb $5S_{1/2} \rightarrow 7S_{1/2}$ transition. The derivativelike line shape from the frequency-modulation technique and the following noise show the laser frequency locked.

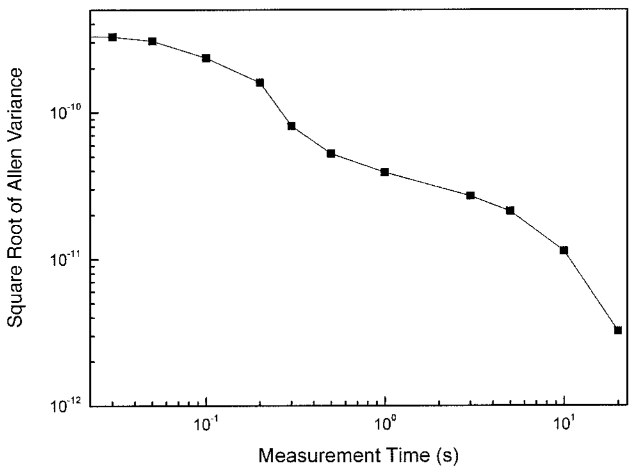

Fig. 4. Square root of the Allan variance as a function of measurement time.

In conclusion, for the first time to our knowledge the two-photon transition of rubidium $5S_{1/2} \rightarrow 7S_{1/2}$ was observed by use of light source from a PPLN waveguide pumped by an erbium-doped fiber amplifier–amplified extended-cavity diode laser. The efficient SH generation conversion leads to a good signal-to-noise ratio and permits direct locking of the laser frequency to the Rb $5S_{1/2} \rightarrow 7S_{1/2}$ two-photon transition. The compact experimental scheme eliminates the need for an enhancement cavity or for beating with another laser at 760 nm. The scheme enables one to achieve high-performance portable frequency standards in the 1520-nm region. Its insensitivity to magnetic field makes the new scheme preferable to the currently recommended standard, the Rb $5S_{1/2} \rightarrow 5D_{5/2}$ transition at 778 nm[3]. The currently observed linewidth, which is due mainly to the laser linewidth, can be further narrowed by use of a laser system with a smaller frequency jitter, such as a stabilized diode laser or a Ti:sapphire laser. One can measure the absolute frequency by beating with a femtosecond comb generated from a frequency self-locked femtosecond laser. This measurement is now being made at the Laser Spectroscopy Laboratory, National Tsing Hua University.

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