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Frequency stabilization of a frequency-doubled 197.2 THz distributed feedback diode laser on rubidium $5S_{1/2} \rightarrow 7S_{1/2}$ two-photon transitions

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Abstract

A 197.2 THz (1520.2 nm) ITU-T grid distributed feedback (DFB) diode laser is frequency stabilized at 197.198 THz by locking its second harmonic (SH) signal on the rubidium $5S_{1/2} \rightarrow 7S_{1/2}$ two-photon transition at 394.396 THz (760.1 nm). With 100 mW from the DFB diode laser and amplifying by an erbium-doped fiber amplifier, we obtain an SH power of 15 mW using a periodically poled lithium niobate (PPLN) waveguide frequency doubler. The stability was 2×10^{-11} (10 s), corresponding to a frequency variation of 4 kHz at 1520.2 nm. Our scheme provides a compact and high performance frequency reference in the communication band.
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Keywords: Frequency stabilization; Rubidium; Two-photon spectroscopy; Nonlinear optics; WDM systems

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Absolute frequency-stabilized diode lasers within telecom band are required for frequency references in dense wavelength division-multiplexed (DWDM) optical communications systems and related instrumentation [1]. Atomic or molecular absorption lines provide wavelength references that are essential for the calibration of channel allocation. Many sub-Doppler lines have been observed using saturated absorption techniques with molecules such as C_2H_2 [2,3] and HCN [4], and provide adequate references for this purpose. An alternative approach is to utilize Doppler-free atomic transitions at the frequency of the second harmonic (SH) signal of the laser as frequency references. Saturated transitions of rubidium at 780 nm have been observed using the second harmonic of a 1560 nm laser and successfully used for frequency-locking purposes [5]. Higher stability and accuracy are provided by Rb 5S–5D two-photon transitions at 778 nm [1,6,7], because of their narrow natural linewidth. However, for 5S–5D transitions, due to the difference of the Landé g factors between S and D states, the magnetic field must be carefully shielded to avoid any possible shift of transition centers caused by Zeeman effect [7]. Another potential candidate is the Rb 5S–7S two-photon transition at 760.1 nm. Although the signal strength of Rb 5S–7S transitions is only $\frac{1}{100}$ of that of Rb 5S–5D transitions, the 5S–7S transitions are free from such Zeeman shifts [8] since both the lower and upper levels have the same Landé g factors, and therefore do not require magnetic shielding. In comparison with the recommended standard, the 5S–5D transition, the insensitivity to magnetic field makes it more preferable.

Recently, Ko and Liu [8] used a 6 mW 760 nm external cavity diode laser (ECDL) to observe rubidium 5S–7S two-photon transitions. Signals with good signal-to-noise ratio (SNR) were detected. In our group [9], for the first time, the two-photon transition of rubidium 5S–7S was observed using a second harmonic light source from a periodically poled lithium niobate (PPLN) waveguide pumped by an erbium-doped fiber amplifier (EDFA) that amplified the output of an ECDL. The efficient second harmonic generation (SHG) conversion leads to a good SNR, and allows direct locking of the laser frequency to the Rb 5S–7S two-photon transition.

Compared to ECDLs, distributed feedback (DFB) diode lasers are compact, low cost and easy to control. They are widely used in practical optical communication systems. Although a DFB laser has a narrow tuning range (~3 nm), one suitable DFB laser diode can cover all of rubidium 5S–7S transitions since the hyperfine splitting of rubidium 5S–7S two-photon transitions is only 3.1 GHz [8]. In this article, a 197.2 THz DFB diode laser was directly frequency locked on the rubidium 5S–7S two-photon transition. With a measurement time of 10 s, the stability was 2×10^{-11}, which corresponds to a frequency variation of 4 kHz at 1520.2 nm.

The experimental setup is shown in Fig. 1. The laser source is a commercial S-band ITU-T grid DFB diode laser (NLD1556STG, NTT Electronics) of 197.2 THz [10]. The laser line width is less than 2 MHz. The laser wavelength can be tuned by varying the operation temperature (0.11 nm/°C) and the laser driving current (5.84 pm/mA). The 20 mW output power was amplified to 100 mW using an erbium-doped fiber amplifier. A fiber polarization controller rotated the laser polarization direction at the fiber output to be parallel to the extraordinary axis of the PPLN crystal. The beam size was adjusted using an optical telescope, for optimal coupling

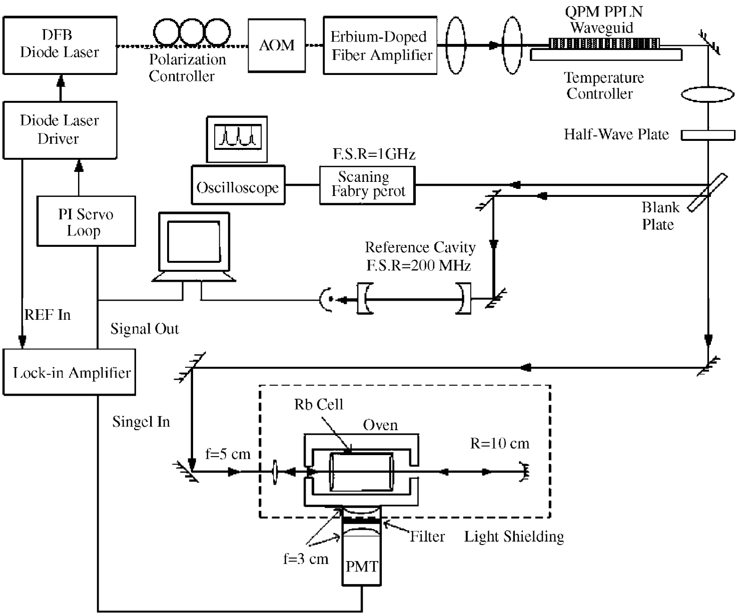

Fig. 1. Experimental setup for the frequency locking of the 1520 nm distributed feedback diode laser. PMT, AOM, PI servo loop, QPM PPLN: quasi-phase matched PPLN.

into the PPLN waveguide. The temperature of the waveguide device was kept at 105.8 °C using a temperature controller (Lakeshore 340) to meet the quasi-phase matching (QPM) condition.

The PPLN waveguides used in the experiment were 52 mm long with a 46 mm poling region and 1.5 mm long mode filters (single mode waveguide segments) and tapers on each side. Mode filter widths ranging from 3 to 6 μm were used to allow flexibility in the mode matching on the input and output of the waveguides. The poling period was 15 μm with duty cycle of $50 \pm 5\%$. The reverse proton exchange (RPE) method was used for fabrication [11]. The periodically poled chip was proton exchanged in benzoic acid at 160 °C for 23.8 h to a depth of 1.22 μm, then annealed in air at 312 °C for 19.9 h and reverse proton exchanged in a eutectic melt of lithium nitrate, sodium nitrate and potassium nitrate [12] at 301 °C for 21.7 h. The typical internal SHG conversion efficiency of the waveguides was in the range 90–100%/W cm^2 with propagation losses of 0.27–0.4 dB/cm. Non-critical phase-matching was obtained for waveguide width of 6.5 μm. The phase-matching wavelength at room temperature was 1508.7 nm.

The optical power of the SH signal was typically 15 mW. After the PPLN waveguide, the SH beam was collimated to a beam waist of 0.5 mm using an, $f = 25$ mm, plano-convex lens. A small portion of the laser beam picked up using a glass plate was separately sent to a scanning Fabry–Perot interferometer for laser scanning diagnosis and to a reference cavity with a FSR of 200.0 MHz for frequency calibration. The absolute frequency of the laser was measured using a wavemeter with a GHz accuracy. The 15 mW laser beam was focused to a beam diameter of 50 μm in the middle of the cell using an AR coated lens with $f = 50$ mm. The transmitted beam was reflected back into the cell by a highly reflective spherical mirror with a 100 mm radius of curvature.

The rubidium cell (Toptica CE RB 25) with a length of 25 mm was contained in an aluminum box, and heated using two thin heating sheets. The finger of the cell protruded out of the container through an opening hole was kept at the temperature 25 °C lower than that of the rest of the cell. The typical temperature of the cell finger in this work was 110 °C corresponding to a vapor pressure of 67 mPa and a number density of $1.61 \times 10^{19}\,\mathrm{m}^{-3}$. The 420 nm fluorescence was collimated, and then passed through a 420 nm dielectric bandpass filter to reduce the background noise caused by the scattered laser light. The fluorescence was measured using a photo multiplier tube (PMT) with a 20 MΩ load resistor and a lock-in amplifier. A PC simultaneously recorded the two-photon signal and the fringes of the reference cavity. A light shield covered the entire apparatus in order to avoid any disturbance from room light.

The spectrum of two-photon transition is shown in Fig. 2, where the laser intensity was chopped at 5 kHz using an acousto-optic modulator. The transition linewidth is 4.5 MHz at 760.1 nm, which is larger than the natural linewidth. And the linewidth was twice that of the spectrum using an ECDL in the previous work [8]. The linewidth broadening was mainly due to the linewidth of the DFB diode laser.

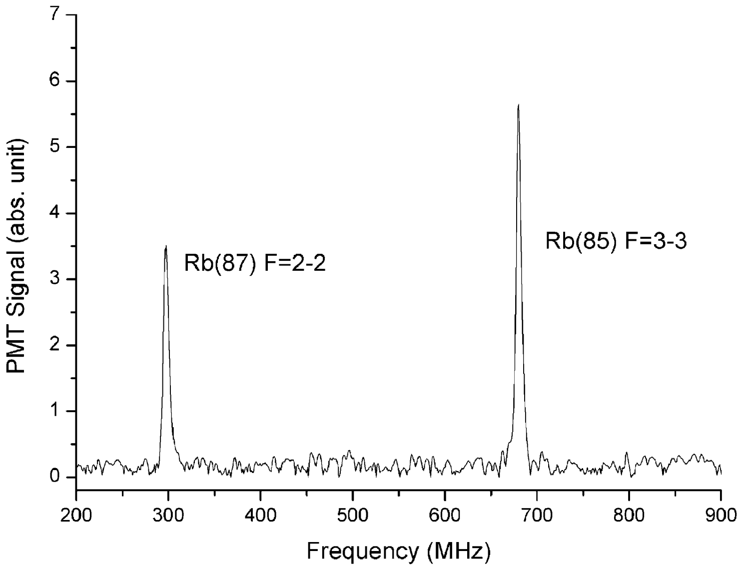

Fig. 2. The spectrum of Rb(87) (F = 2-2) and Rb(85) (F = 3-3) two-photons transitions. The linewidth is 4.5 MHz at 760.1 nm.

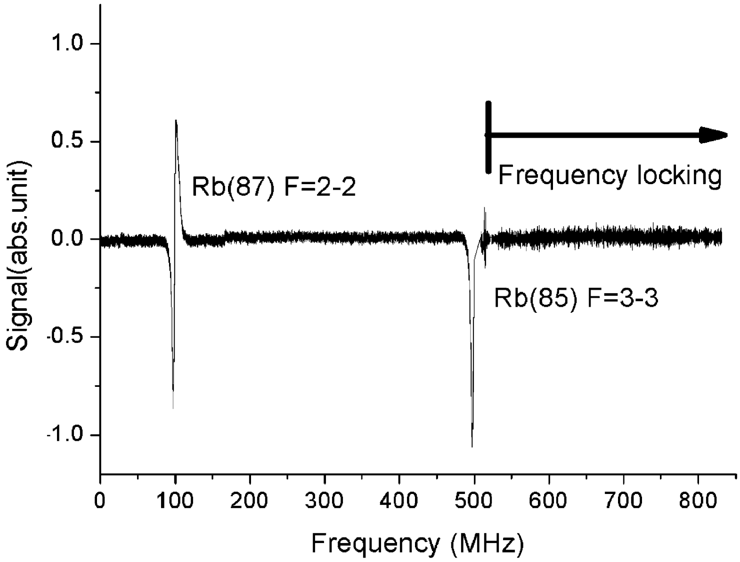

Fig. 3. The dispersion-like signals of Rubidium two-photon transition Rb(87) (F = 2-2) and Rb(85) (F = 3-3). The error signal of time trace after laser frequency locking.

In order to obtain a dispersion-like lineshape for frequency stabilization on the atomic transition, we performed the wavelength modulation spectroscopy. A typical dispersion-like lineshape is shown in Fig. 3 where the modulation depth was 8 MHz and the modulation frequency was 80 kHz. The wavelength modulation was introduced by directly modulating the current of the DFB diode laser. The signal width (peak-to-peak) was 10 MHz. The SNR was 30 using a 10 ms lock-in time constant. To stabilize the laser frequency, the zero-crossing signal was fed to the diode laser driver through a proportional-integral (PI) servo loop. A time trace of the error signal when the laser was locked is also shown in Fig. 3. The laser was locked on the Rb(85) F = 3-3 two-photon transition, the frequency jitter (peak-to-peak) was 0.34 MHz at 760.1 nm.

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 2×10^{-11}, which corresponds to a frequency variation of 4 kHz at 1520.2 nm.

We stabilize the frequency of a 197.2 THz ITU-T grid DFB laser diode on 197.198 THz by locking its SH signal on the rubidium 5S–7S two-photon transition. The frequency, 197.200 THz, is one channel of dense WDM frequency grid recommended by International Telecommunication Union [10]. The stabilized frequency is only 2 GHz away from the nearby ITU-T grid frequency 197.200 THz. With appropriate offset frequency locking, we can lock the frequency of other DFB diode lasers on 197.2 THz with high accuracy. At presence, the frequency jitter at

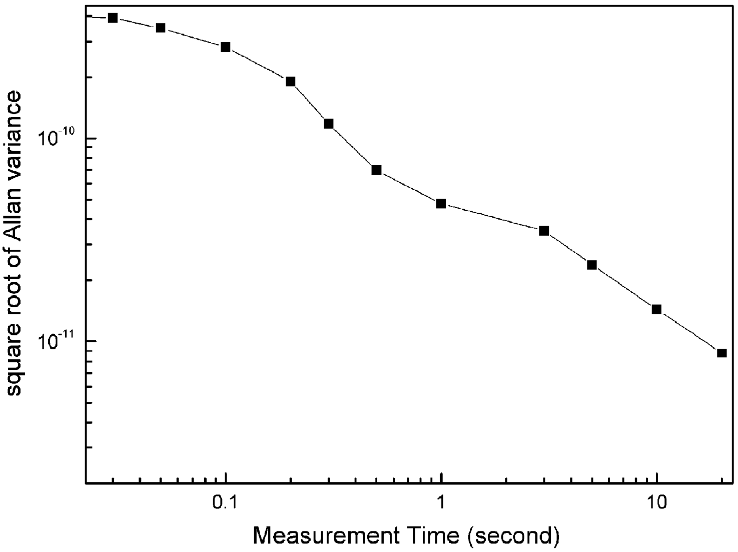

Fig. 4. Square root of the calculated Allan variance as a function of measurement time.

10 ms lock-in time constant was 0.34 MHz at 760.1 nm, i.e. 0.17 MHz at 1520.2 nm. The stability at 1520.2 nm was better than 2×10^{-11} with a measurement time of 10 s.

The efficient SH conversion using PPLN waveguide led to a good SNR, and allowed to directly lock the laser frequency to the rubidium 5S–7S two-photon transition. The experimental scheme eliminates the need for an enhancement cavity [7], or beating with another frequency-stabilized laser at 760 nm. This scheme enables one to realize high-performance portable frequency standards in the 1520 nm region, and suitable to be integrated into DWDM system for on-line frequency calibration systems. The insensitivity to magnetic field makes the new scheme preferable, comparing with the currently recommended standard, rubidium $5S_{1/2} \rightarrow 5D_{5/2}$ transition at 778 nm. The currently observed linewidth, which was limited to the laser linewidth, can be reduced using a DFB diode laser with external cavity [13]. This system together with a frequency-stabilized DFB diode laser at 192.6 THz (1556 nm) that is frequency locked by locking its SH signal on rubidium $5S_{1/2} \rightarrow 5D_{5/2}$ transition at 778 nm [7] can provide an accurate two-point calibration for optical communication band.

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