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Development of an optical frequency comb around 1556 nm referenced to an Rb frequency standard at 778 nm

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Abstract. To transfer and expand in the optical telecommunication range the accurate $5S_{1/2}(F=3)$ – $5D_{5/2}(F=5)$ rubidium frequency reference at 778 nm (385.285 THz), we employ a second harmonic generation (SHG) process coupled to an optical frequency comb (OFC) both based on the use of a low power and narrow linewidth laser diode operating around 1556 nm. The Rb optical frequency reference is known with an accuracy of 2.6×10^{-12} and exhibits a frequency stability of $4 \times 10^{-13}\tau^{-1/2}$, with a Flicker plateau of 2×10^{-14} for $\tau > 200$ s. With 20 mW of laser power at 1556 nm, we perform a SHG process in a periodically poled lithium niobate (PPLN) crystal and we obtain 6.5 μW of harmonic radiation at 778 nm, used to phase lock the IR laser against a Rb optical frequency standard (OFS). This Rb-referenced fundamental radiation at 1556 nm is duplicated as 34 lines spaced by 10 GHz using an electro-optic phase modulator (EOM). This preliminary result is mainly limited by unexpected high optical losses in the Fabry Perot cavity, which comprises the EOM.

PACS. 32.80.Qk Coherent control of atomic interactions with photons – 42.65.Ky Harmonic generation, frequency conversion – 42.72.Ai Infrared sources

1 Introduction

The requirement of accurate frequency reference for atomic spectroscopy and frequency/length metrology has motivated at the beginning of the last decade the development of laser diode frequency stabilized to atomic rubidium Doppler-free two-photon transition at 778 nm [1,2]. Fortunately, the frequency of the Rb optical frequency standard (OFS) is very close to the fourth sub harmonic of 2S-nS transition of hydrogen and deuterium atoms allowing the improvement of the Rydberg constant value by the Biraben's group [3].

Due to its low cost and intrinsic high metrological performances, this frequency standard is now proved to be a very promising alternative to replace the popular He-Ne/I_2 laser at 633 nm. Thanks to the narrow linewidth of the Rb two photon transition (~500 kHz) and its low sensitivity to external parameters, the gain in term of both accuracy and stability is at least one order of magnitude. At present time, this Rb OFS operating at 778 nm is one of the recommended radiations by the Comité International des Poids et Mesures (CIPM) for the *mise en pratique* of the definition of the meter [4].

Moreover, the interest of that standard is enlarged by the possibility to transfer the Rb performances to the 1.5 μm range in a simple way *via* a second harmonic generation process in non-linear crystals, such as $LiNbO_3$. This easy-use is extremely useful in the field of optical communications systems, for the calibration of channel allocation in dense wavelength-division-multiplexed (WDM) systems and related instrumentation [5,6]. The major laser systems locked to atomic or molecular transitions operating in the 1.5 μm range suffer from the broad and/or weak absorption signals for the locking purpose [7,8]. Then, the performances are limited to few parts in 10^{-9}.

The use of the half frequency of the Rb two photon reference operating at 778 nm ($\nu \sim 385.285$ THz) which presents a narrower linewidth (~500 kHz) than the one directly accessible at 1.5 μm, opens the way to realize frequency measurements with an accuracy in 10^{-12} range and a frequency stability of 4×10^{-13} for 1s integration time. Another possibility consists on the use of the Rb D_2 line at 780 nm as an alternative reference that needs only about 1 μW to saturate the atomic transition [9–11]. The performances are reduced to the 10^{-9}–10^{-10} ranges, but the experimental set-up is compacted and simplified.

Our system is divided in three independent parts, as illustrated in Figure 1 and detailed in the following sections.

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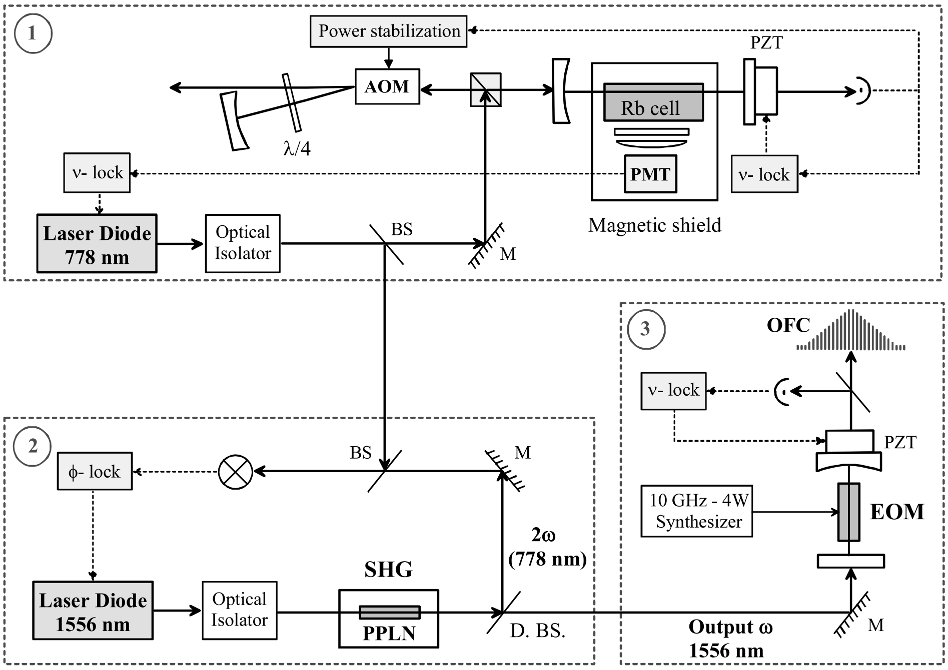


Fig. 1. Diagram of the experimental set-up. Part 1: Rb optical frequency standard set-up; Part 2: SHG in a PPLN crystal; Part 3: OFC based on the use of an EOM placed inside a Fabry-Perot cavity. AOM: Acousto-Optic Modulator; PMT: Photomultiplier Tube; PZT: Piezoelectric transducer; BS: Beamsplitter; D. BS: Dichromatic Beamsplitter; M: Mirror; ν-lock: frequency lock; Φ-lock: phase lock.

The first part (1) describes the Rb two-photon frequency reference operating at 778 nm. Indeed, more than 10 different hyperfine components of the $5S_{1/2}$-$5D_{3/2}$ and $5S_{1/2}$-$5D_{5/2}$ Doppler-free two-photon transitions could be efficiently used as frequency references over 45 GHz frequency span around 385.285 THz (778 nm).

The second parts (2) is devoted to the SHG process of a 1.5 μm radiation in a $LiNbO_3$ crystal, and the link with the Rb OFS using phase lock technique. This use allows us to overcome the difficulty to use the poor level of the second harmonic power, which is not sufficient to probe directly the Rb two-photon resonance at 778 nm. For this excitation a few mW are required to get enough signal-to-noise ratio (S/N) for the frequency stabilization purpose.

The last part (3) is devoted to the achievement of an optical frequency comb spaced by 10 GHz around 1556 nm. This technique has been demonstrated in early 1990's in the field of broadband frequency measurements and optical communication developments [12].

2 The Rb frequency reference set-up

This optical frequency standard is described in more details elsewhere [13,14]. The laser diode is set in an extended cavity configuration (ECLD), using a 1200 grooves/mm grating supported by a piezo electric transducer (PZT) to control the 10 cm length cavity (1.5 GHz free spectral range). The ECLD is placed inside a regulated temperature metal box (around 30 °C) itself inserted in a press wood box to insure a good acoustic isolation. The laser linewidth of the ECLD is measured as 50 kHz, by beating two similar devices. After passing a 60 dB isolation Faraday isolator, the laser beam is sent in an acousto-optic modulator, used in a double pass configuration. This use permits us to enhance the optical isolation of the ECLD and also to stabilize the optical power inside the Fabry-Perot (FP) cavity containing the natural Rb cell (73% of ^{85}Rb and 27% of ^{87}Rb). The plano-concave FP cavity ensures to probe the Rb transitions, with a well-defined Gaussian beam ($I = 30$ mW, $\pi\omega^2 \sim 1$ mm^2) and facilitates the accurate determination of the power level used to probe the atomic transition. Furthermore, we can well characterize the frequency shift due to the ac Stark effect, which is the main effect that affects the centerline of the Doppler free two-photon resonance.

The temperature of the Rb cell is stabilized around 90 °C in order to obtain a Rb pressure about 8×10^{-5} torr. In this situation the loaded FP cavity finesse is about 50. The detection of the well-resolved hyperfine components of the Rb Doppler free two-photon transitions is performed by monitoring the blue fluorescence signal ($\lambda = 420$ nm) due to the radiative cascade 5D-6P-5S, using a photomultiplier tube. The demodulated signal at 70 kHz is used to lock the laser frequency to the center of the Rb line, by reacting on the laser diode current and the PZT supporting the grating. The whole device (FP + Rb cell + PMT) is surrounded by a magnetic shield in order to reduce the influence of external magnetic fields. The Rb transitions exhibit a typical linewidth of about 500 kHz. Three stationary similar systems have been built in early 1990's.

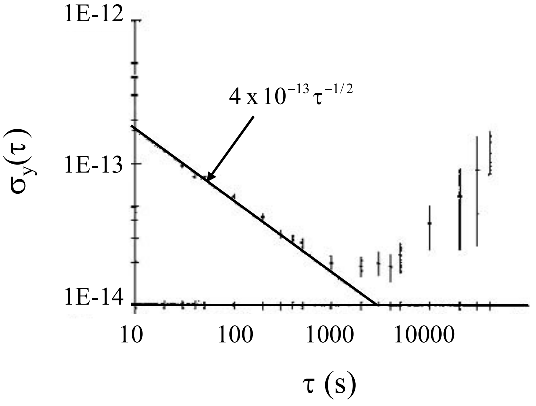


Fig. 2. Allan standard deviation of the beatnote between two similar and independent Rb optical frequency standard at 778 nm.

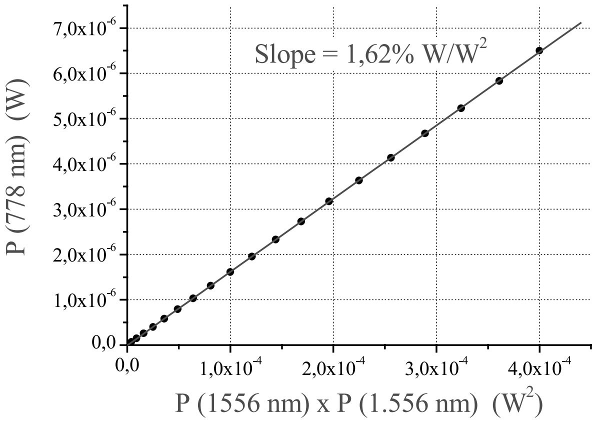


Fig. 3. Variation of the SH power at 778 nm *versus* the fundamental power square at 1556 nm.

Two are located at BNM-LPTF at Observatoire de Paris; the third one at LKB laboratory at the University Pierre & Marie Curie. The latter is connected to the LPTF by two 3 km long optical fibers, used for frequency comparisons. A frequency discrepancy of 1 kHz ($\Delta\nu/\nu \sim 2.6 \times 10^{-12}$) between the three systems has been measured and is constant over several years within less than 1 kHz [14]. The collisions between Rb atoms and foreign gas are responsible for the observed frequency differences.

The absolute frequency measurements of these three Rb-systems have been performed in 1996, using a complex frequency multiplication chain for the link to cesium atomic clock at BNM-LPTF [13]. This work has been achieved in the frame of a scientific collaboration between the BNM-LPTF and the LKB laboratories. These Rb optical frequency standards (OFS) have been applied to the measurements of several hydrogen and deuterium frequency transitions and to the new determination of the Rydberg constant [3].

More recently, a fourth system similar to the precedent ones, but more compact and designed as transportable frequency standard has been built and uses a Rb cell filled 7 years later with also natural mixture. It exhibits 5 kHz-discrepancy when compared to the three precedents Rb-OFS. This frequency disagreement is also constant within 500 Hz over 2 years. This frequency difference is probably due to possible collisions with foreign gas in the cell. The full dispersion (5 kHz) of these four Rb OFS is in agreement with other independent measurements reported elsewhere [15]. The behavior of the frequency of the transportable Rb OFS has been checked before and after a round trip (France-Japan-France) organized in the frame of an international frequency comparison [16]. When compared to our stationary Rb OFS, the frequency of that transportable system is reproduced within 500 Hz. These fourth systems developed in Paris, exhibit similar frequency stabilities given by the Allan standard deviation as $4 \times 10^{-13}\,\tau^{-1/2}$ with a Flicker plateau of 2×10^{-14} for $\tau > 200$ s (Fig. 2).

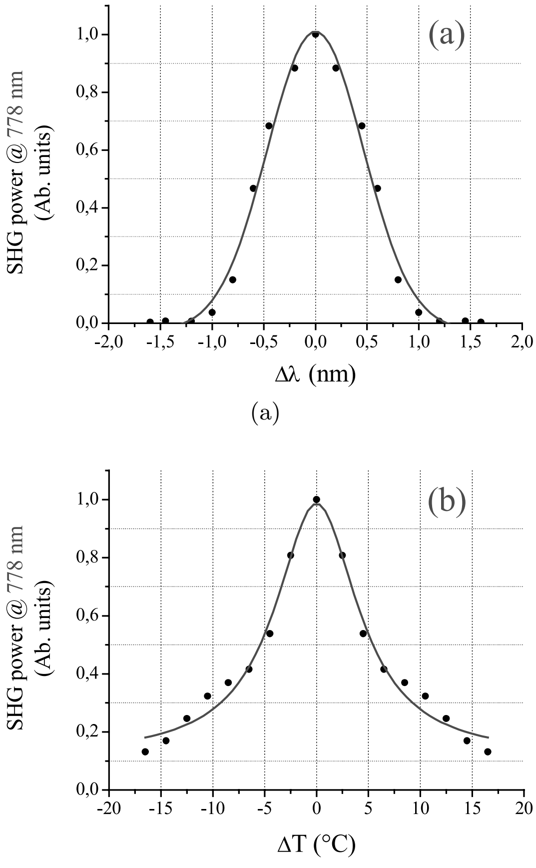
3 The SHG process at 1556 nm

We use a commercial 1.5 μm ECLD (Tunics PR 1550/Photonetics) which delivers up to 20 mW output power from 1500 to 1600 nm. By monitoring the beatnote between two similar devices, we have measured the linewidth as lower than 100 kHz. A plano-convex lens (focal 100 mm) is used to focus the light beam into the periodically poled lithium niobate (PPLN) crystal to achieve the second harmonic process. After passing a dichroic beamsplitter, the issued radiation at 778 nm serves to phase lock the 1.5 μm ECLD with respect to the Rb OFS, while the fundamental radiation is used to generate the frequency comb around the half Rb frequency. The two faces of the 19 mm long PPLN crystal (multigrating period from 18.6 μm to 20.4 μm) have been antireflection coated at both fundamental and harmonic wavelengths. The sample is heated at 65 °C to achieve the optimum second harmonic process at 1556 nm using the 19 μm period grating.

We report in Figure 3 the variation of the second harmonic power as a function of the power square at 1556 nm. With an incident power of 20 mW at 1556 nm, we obtain 6.5 μW of power at 778 nm, which corresponds to 1.62% W/W^2 single-pass conversion efficiency and gives an experimental value $d_{\text{eff}} = 19.8$ pm/V. The power level achieved by this SHG process is sufficient for detecting the sub-Doppler D_2 line of Rb at 780 nm as demonstrated in reference [10].

Figures 4a and 4b illustrate the wavelength and the temperature dependences, giving an acceptance bandwidth (FWHM) of 1.1 nm and 8 °C respectively. This last result demonstrates the non-critical phase matching condition with respect to the temperature.

We have mixed only 1 μW of second harmonic power with 450 μW power from the Rb OFS in an avalanche photodiode and we have obtained a beatnote with more than 40 dB of signal-to-noise ratio (SNR) in 300 kHz resolution bandwidth. This SNR is sufficient to phase lock the laser diode at 1556 nm against the Rb OFS with a servo-loop



(a)

(b)

Fig. 4. Wavelength and temperature acceptances.

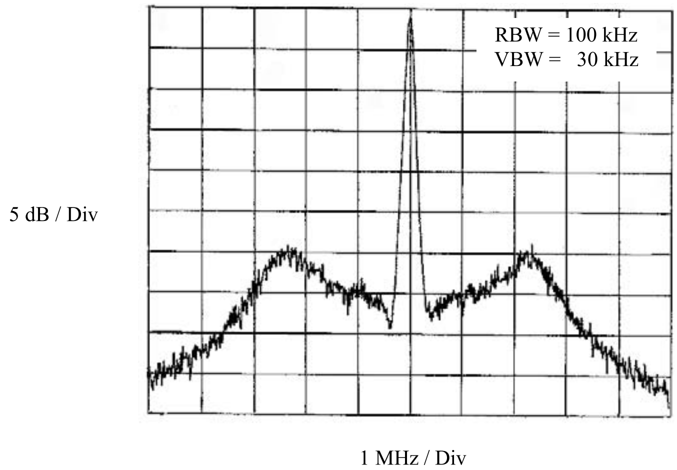


Fig. 5. Beatnote between the Rb optical frequency standard at 778 nm and the frequency doubled 1556 nm ECLD.

bandwidth of 2 MHz (Fig. 5). This phase lock operation permits us to transfer the metrological performances of the Rb OFS to the 1556 nm ECLD.

4 Development of an OFC at 1556 nm

This system is based on the use of a high frequency resonant electro-optic modulator (EOM), placed inside a high finesse Fabry Perot cavity (FP). The free-spectral range of that cavity is chosen equal to an integer sub harmonic of the microwave frequency modulation (10 GHz in this case). In this way, the FP is resonant in a same time with the carrier and all the successive sidebands produced by the EOM.

Up to 4 THz frequency difference has been already measured in the 1.5 μm range, between two ends of an OFC produced by a high frequency resonant electro-optic modulator inserted in a Fabry-Perot cavity [12]. In principle, the width of this kind of OFC is only limited by the system dispersion [17], and its power spectrum is given by:

$$P_k = \eta_{\mathrm{FP}} P_{\mathrm{in}} \left(\frac{\pi}{2\beta F}\right)^2 \exp\left(-\frac{|k|\pi}{2\beta F}\right)$$

P_k is the power of the kth sideband, P_{in} the incident power, β is the modulation index, F and η_{FP} are the finesse and the peak transmission respectively, measured when the microwave power is switched off.

This expression shows that a high finesse and a large modulation index are necessary to transfer a high optical power to the far sidebands. The use of a three mirrors-cavity to increase the optical power coupling has been proposed to enhance the frequency comb with an important optical power transferred to the sidebands [18].

We have used a conventional interaction scheme utilizing a high finesse FP cavity ($F \sim 650$), before introducing the EOM), which consists of an input plane mirror and an output mirror of 400 mm of radius of curvature. A PZT ceramic supporting the output mirror is dithered at 4.5 kHz and used to stabilize the FP length using a part of the transmitted signal (10%), after demodulation, in order to maintain a permanent resonance with the incident frequency.

The distance between the mirrors is chosen to match the twelfth subharmonic of the EOM frequency (10 GHz). The radiation issued from the SHG set-up (10 mW) is matched to the FP cavity using appropriate lenses. The EOM is placed at 45 mm from the output mirror in order to ensure that the propagating wave in the cavity encounters the same microwave phase for each pass through the modulator. Monitoring a beatnote between a far sideband and an auxiliary ECLD operating at the same frequency has optimised this position.

When the EOM has been introduced in the FP cavity, the finesse and the transmission have been dramatically reduced to 80 and 0.1% levels respectively. On the other hand, using a 4 W microwave power, the modulation index β was found to be 0.06 only. Under these conditions we did not observe sidebands beyond the 17th harmonic of 10 GHz microwave excitation.

Figure 6 reports the evolution of the SNR of the successive beatnotes between the output of the OFC set-up and an auxiliary 1.5 μm ECLD radiation in a fast InGaAs photodiode. The frequency of this additional ECLD

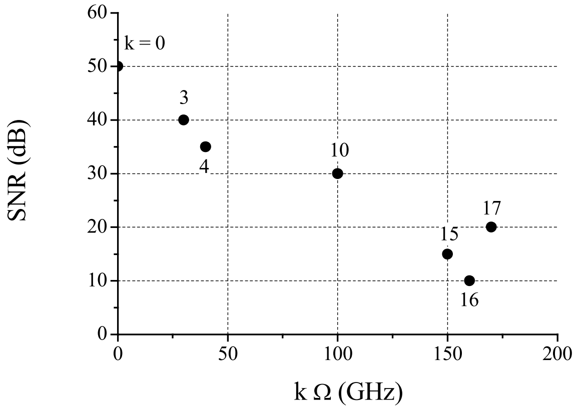


Fig. 6. SNR of the beatnotes between the OFC and the tuneable auxiliary laser diode around 1556 nm.

is varied (and accurately controlled with a lambdameter) over 340 GHz around the half frequency Rb-reference.

These results – although modest – illustrate the possibility to develop an useful frequency comb around 1.5 μm, which performances in term of accuracy and frequency stability are in the 10^{-12} and 10^{-13} ranges respectively. A broadband OFC could be achieved in near future by utilizing a low losses optical cavity and a higher modulation index. The use of a secondary coupling mirror as mentioned above could be also introduced for this purpose.

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