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Methods and evaluation of frequency aging in distributed-feedback laser diodes for rubidium atomic clocks

Renaud Matthey,* Christoph Affolderbach, and Gaetano Mileti

Laboratoire Temps-Fréquence, University of Neuchâtel, Avenue de Bellevaux 51, 2000 Neuchâtel, Switzerland
**Corresponding author: renaud.matthey-de-lendroit@unine.ch*

Distributed-feedback laser diodes emitting at 780 nm have been evaluated, with respect to the aging of the injection current required for reaching the rubidium D2 resonance line. Results obtained for lasers operating in air and in vacuum for 9 months are reported. When operated at constant temperature, the laser current required for emission at the wavelength of the desired atomic resonance is found to decrease by 50 to 80 μA per month. The impact of this result on the lifetime and long-term performances of laser-pumped rubidium atomic clocks is discussed.

Reliable single-mode and narrowband laser diodes are required for a wide range of applications and precision instrumentation including atomic clocks [1–3], magnetometers [4], precision gyroscopes [5], trace gas sensing [6], and telecommunication. The reliability and lifetime of such instruments critically relies on the same characteristics of the laser diodes implemented [7,8]. A variety of tests were established [9] and are now routinely performed on laser diodes, both for applications on ground [10] and in space [11,12].

Standard procedures on laser reliability testing include the laser linewidth and the intensity noise [9], but other spectral properties parameters relevant for high-precision instrumentation using narrow atomic resonances, such as atomic clocks and gyroscopes, are not considered, e.g., frequency noise or aging of the injection current required to reach a specific wavelength. Here we report on our studies on the aging of the *current at resonance* for distributed-feedback (DFB) laser diodes, which emission at 780 nm corresponds to the Rb D2 transition, as used in Rb atomic clocks. This current is understood as the injection current (at constant laser chip temperature) needed to maintain the laser emission precisely at the center of the atomic resonance. The aging of this current, or *frequency aging*, can limit the spectral lifetime of the laser and finally also the instrument lifetime, because at some time it can become impossible to maintain the Rb resonance wavelength by simply adjusting the laser current. Measurement of the laser wavelength throughout the aging procedure was previously applied to a 780 nm vertical-cavity surface-emitting laser (VCSEL) [7] and in radiation tests on DFB at 1.55 μm [11], but two-point measurements (before and after aging) are predominant in the literature [12–14]. In this Letter, we report on aging of the current at resonance, measured several times per day over many months.

The lasers under study are GaAs DFB laser diodes (Eagleyard Photonics, EYP-DFB-0780-00080-1500) [15]. They emit at 780 nm. Three devices were evaluated on the long-term. Two were packaged in a TO-9 can style with integrated monitor diode, while the third one was in a TO-3 housing with a thermoelectric cooler (TEC) and thermistor (NTC) additionally integrated.

Two different methods were applied to evaluate the frequency aging of the devices; both imply an Rb D2 transition at 780 nm as frequency discriminator. In the first method, the laser beam passes through a cell that contains an Rb vapor and is collected by a detector placed after the cell. The laser diode current is swept to scan the atomic resonance. The resonance current is then retrieved from the measured absorption spectrum. The Rb cell acts as reference and provides intrinsic long-term stability. In the second method, the laser is stabilized to the Rb transition through a locking scheme based on wavelength modulation spectroscopy and built around a lock-in amplifier and an Rb cell as frequency discriminator. The injection current is continuously adjusted by the feedback loop to maintain the laser frequency at the center of the transition. So, the laser always operates at the resonance current.

A laser diode spectral aging system was assembled from off-the-shelf components with the ability to characterize a variety of laser diodes (DFB lasers, VCSEL's, Fabry–Perot, or similar lasers) mounted in various housings and emitting at Rb resonance wavelengths. The system allows measuring parameters like current at resonance (according to the first method), threshold current, frequency and optical power tuning rates versus current and temperature, and, with additional laboratory instruments, relative intensity noise (RIN), frequency noise, and laser linewidth.

As schematically illustrated in Fig. 1(a), the system contains a computer-driven platform (Thorlabs PRO8000), which integrates modules (Thorlabs ITC8000 series) controlling the laser diode temperature and injection current. It measures and records currents from photodetectors and laser parameters (temperature, current, voltage) too. Depending on the laser diode package, different mounts are used (all from Thorlabs). Mirrors and beam splitters guide the laser beams through an ^{87}Rb enriched vapor gas cell, temperature-stabilized at 45.0 °C (54% absorption for the $F = 2$ component). The optical part of the setup, including the laser diodes and their mounts, is placed in a protective box to isolate it from the air convection in the lab room due to the air-conditioning system. The box additionally prevents dust from depositing on the optical system and limits the background light influence.

Two laser diodes, LD1 and LD2, are implemented and tested in the aging setup, one for each package, with and without integrated Peltier element, respectively. The aging of their current at resonance is retrieved, applying the first method described above, from current scans [Fig. 1(b)] automatically repeated at regular time intervals.

The second method was applied to the frequency aging evaluation of a TO-9 DFB laser diode, LD3, installed in a 0.2 l compact laser head [16] operated under vacuum, at 10^{-6} mbar level. The laser head includes frequency stabilization to Doppler-free saturated-absorption resonances of the ^{87}Rb D2 lines. Beat-note between two similar laser heads showed relative laser frequency stability below 10^{-11}, i.e., less than 4 kHz, from 1 s up to 1 day, enough to detect frequency changes at the level of 100 kHz/day.

Before launching the frequency aging measurements of LD1 and LD2 with the laser aging setup in air, they underwent a burn-in process of more than 500 hours. The Rb D2 resonance was reached at an injection current of ∼104 mA at a temperature of 26.5 °C for LD1, and ∼102 mA at 31.0 °C for LD2. Their current thresholds were 37.0 mA and 35.0 mA, respectively. The laser aging setup automatically performed for each laser a current scan of the Rb spectrum each 3 hours during 288 days (except 20 days during which the lasers were still kept running). The injection current resolution was 15 μA. During the whole period, the temperatures of the lasers, more precisely their temperature settings, were kept constant, 26.5 °C for LD1 and 31.0 °C for LD2. Between two consecutive scans, LD1 and LD2 operated at currents of 108 and 109 mA, respectively; no accelerated aging—by running the lasers at much higher temperature and/or current between two scans—was realized.

The evolution of the current at resonance is first discussed for LD1 [Fig. 2(a)]. As determined from continuous temperature records, the resonance current fluctuations reflect the laboratory temperature variations. For instance, the jump in the measured data since day 249 is due to a change of air circulation in the lab, what lowered the temperature in the box by 1.0 °C, reinforced by an additional −1.1 °C due to a colder winter period. Inside the LD1 package, the thermistor and the laser chip are at slightly different locations, so that the control of the laser temperature by the Peltier element via conductive heat transfer is affected by the ambient temperature.

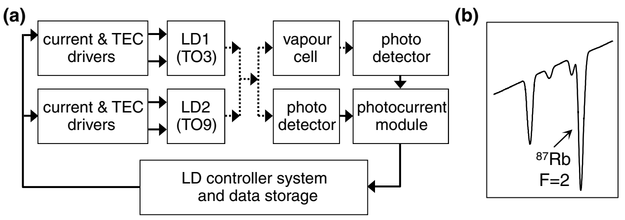

Fig. 1. (a) Schematics of the experimental setup used for the long-term aging tests with two laser diodes (LD1 and LD2). Plain and dotted lines denote electrical connections and optical paths, respectively. (b) Typical enriched ^{87}Rb spectrum obtained by laser diode current sweep. The indicated 500 MHz Doppler-broadened resonance acts as frequency discriminator in the setup.

To estimate the aging of the current at resonance at constant temperature for LD1 [Fig. 2(a)], the measured data were corrected for the variations of the ambient temperature measured in the box—this amounted to separate the direct ohmic heating of the laser gain region through the injection current from the conductive heat transfer [17]. More precisely, the measured current data were fitted by the sum of a second-order polynomial in function of the elapsed time plus a term depending linearly from the variations of the temperature in the box; the temperature-dependant term was then removed to retrieve the effect of aging only. The fit nicely reproduces the measured data. The root mean square (RMS) value of the error between the measured data and the fit is less than 20 μA ($2 \cdot 10^{-4}$ of relative error with respect to the resonance current) over the complete period. The resulting aging rate is −80 μA/month at day 10 and −45 μA/month at day 260. With a frequency tuning rate versus current of −1.3 GHz/mA, as measured for this laser type, it corresponds to a frequency aging of maximum 0.1 GHz/month when the laser is operated at constant temperature and injection current. This is well within the limit of <2 GHz/month reported for 852 nm DFB lasers [14] and of the same order as the ∼17 GHz total shift reported for 848 nm DFB lasers in accelerated testing mimicking 17 years of normal operation conditions [12].

The same procedure was applied to LD2. As neither a TEC device nor a thermistor is integrated in the laser diode package (they are located in the laser mount), the influence of the ambient temperature on the actual temperature of the laser chip is much larger than for LD1, as it

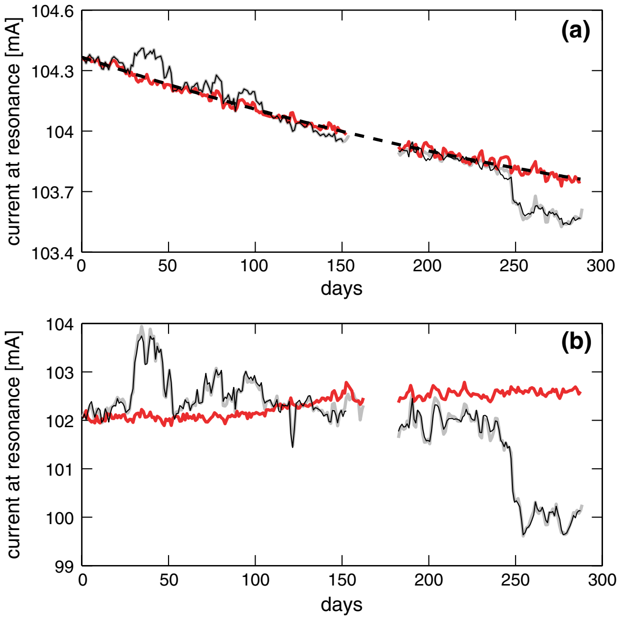

Fig. 2. (Color online) Current at resonance for two DFB laser diodes as measured with the aging system. (a) LD1, with integrated Peltier element, (b) LD2, without such element. The thick light-color solid lines represent the daily averaged measured values; their fits (cf. text) are given by the thin dark solid lines. The values corrected for temperature are given by the thick red solid lines. For LD1, the dashed line is the part of the fit depending only on the elapsed time (second-order polynomial).

can be noticed when comparing Figs. 2(a) and 2(b). To obtain a better temperature correction, the two distinct periods were fitted separately. The RMS error on the fit is 75 μA over the entire aging period. There is no clear tendency over the complete record, even if during the second period the aging process seems to be very slow. The temperature-corrected current at resonance fluctuates within 0.9 mA over the whole record. No mode-hop was observed for any of the laser diodes; it would have resulted in a large change of current.

The third laser diode, LD3, is operated under vacuum, in a thermally controlled chamber, to filter the impact of the laboratory temperature fluctuations. It is exactly of the same type as LD2, packaged without integrated thermistor or TEC element, and with similar specifications. Over 9 months, the laser stayed continuously locked to an Rb Doppler-free transition. Its temperature remained within 6 mK around 31.6 °C. As a result, the aging of the device, −48 μA/month, is clearly evidenced, as illustrated in Fig. 3, even without temperature correction. This value is quite comparable to that of LD1. This consistency between results obtained from different methods and setups, supported by check of the instrumentation and procedures, indicates that the realized observations are not caused by drifts in the instrumentation.

We consider now the use of a DFB laser of similar type as the ones tested in this study or with equivalent specifications in an Rb atomic clock. From an extrapolation of our data to a projected clock lifetime of 20 years, with the assumption of a frequency aging rate of −80 μA/month or −1 mA/year, the current at resonance would thus change from about 100 mA to 80 mA (at constant laser temperature). This is acceptable but also implies a reduction of the laser output power by about 40% over the same time. It thus seems preferable to maintain a constant laser current and correct for the aging of the laser frequency by adjusting the laser temperature (measured tuning rates of −28 GHz/K and −0.4 mW/K). In this case, required adjustment over 20 years is −1 K only, with an associated variation in optical power on the 1% level. Through the intensity light-shift mechanism [1], these variations would induce in an Rb atomic clock a relative frequency drift of $1.7 \cdot 10^{-13}$/month and $4.2 \cdot 10^{-15}$/month, for current and temperature adjustment respectively, assuming an intensity light-shift coefficient of $\sim 10^{-12}/\%$ [2].

In conclusion, we have retrieved the frequency aging of DFB laser diodes, devices used or to be used in atomic clocks. Over 9 months, the current required for the laser to emit at the precise atomic resonance wavelength was found to decrease at a rate of −50 to −80 μA/month (−0.6 to −1 mA/year). As for these devices, the ratio of the temperature tuning rate to the current tuning rate is about 20 K/mA, much larger than the 0.1 K/mA typically observed for VCSELs, the measurements must be performed in environments with high temperature stability, or temperature corrections must be applied. The measured frequency aging rate is low enough to use the DFB lasers in optical pumping for clocks, provided that their spectral aging (linewidth, frequency noise) is also limited. The observed frequency drift can also be compensated by adjustment of the laser temperature (−1 K over 20 years).

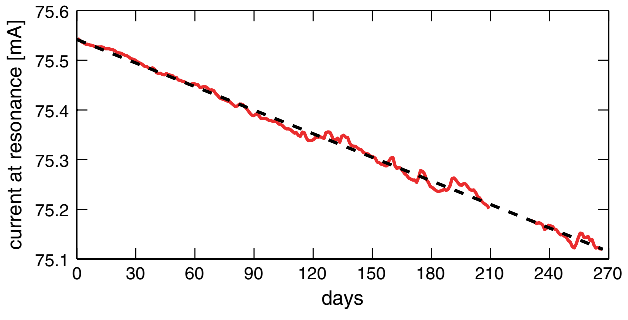

Fig. 3. (Color online) Resonance current for laser diode LD3 operated under vacuum. The solid line represents the measured values. The dashed line is a linear fit to the measured values.

It will be interesting to validate these studies by increased statistics on more samples. More extended studies should also include regular measurements of other laser properties (threshold current, linewidth, RIN, and FM noise) to get a more complete picture of the spectral aging process. Accelerated testing at higher temperature will allow gaining faster insight on the spectral aging.

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