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Multiple wavelength stabilization on a single optical cavity using offset sideband locking technique

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We implemented a compact, robust and stable device for simultaneous frequency stabilization of lasers with different wavelengths used for the cooling and trapping of Yb atoms in an optical lattice clock. The lasers at 399 nm, 556 nm and 759 nm are locked to a single ultra-stable cavity using the offset sideband locking technique, a modified version of the Pound-Drever-Hall method. For the most demanding stabilization here, the 556 nm laser, this system exhibits a 300 Hz linewidth for an integration time of 80 ms. We observed a long term drift of less than 20 kHz per day at 759 nm that is suitable for operating the lattice laser with a light shift uncertainty below 1×10^{-18} . We successfully tested the system for operating the clock during a typical working day by simultaneously locking the three lasers to the cavity. © 2020 Optical Society of America

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Modern atomic manipulation techniques, such as laser cooling and trapping of atoms, rely on locking lasers to an atomic transition or better reference to reduce their linewidth, control the frequency drift and assuring tunability. With commercial laser-linewidths usually ranging from megahertz to a few kilohertz and drifts in the megahertz-region over few seconds, stabilization to an external reference becomes necessary. There are several techniques for implementing stable references such as locking to spectroscopy features or spectral hole burning [1, 2]. For demanding applications optical cavities are commonly used. They offer the possibility of reducing the laser-linewidth to a fraction of the cavity's narrow resonances with equal mode-spacing and robust error-signals, provided for example by the Pound-Drever-Hall (PDH) or Hänsch-Couillaud techniques [3, 4]. The typical cavity's fundamental-mode spacing, namely the free spectral range (FSR), spans from a few hundred megahertz to a few gigahertz and it is defined as $\Delta\nu_{\text{FSR}} = \frac{c}{2L}$ (where L is the cavity length and c the speed of light). The mismatch between the frequency of the cavity and the one actually needed for the experiment is compensated by one or more acousto-optic modulators (AOM) or electro-optic phase modulators (EOM). In the latter case frequency modulation (FM), or serrodyne phase manipulation [5], bridges the large frequency gap. Here we use the offset sideband locking technique [6]. The RF signal sent to the EOM (Ω_{gap}) is phase-modulated (PM) (typically by a smaller modulation frequency

$\Omega_{\text{PDH}} < \Omega_{\text{gap}}$) giving first order sidebands at Ω_{gap} from the carrier and an additional set of sidebands around them spaced by Ω_{PDH} . The latter are used to generate the usual PDH error signal demodulating the cavity's reflected light signal at Ω_{PDH} . This gives the advantage of using a single EOM with high modulation bandwidth (up to several GHz) [6] over a combined AOM/EOM setup with similar performances. Moreover lasers at different wavelengths can be locked to the same reference using for example the transfer cavity technique [7] while the offset sideband technique has been used in a previous work to stabilize different lasers on three optical cavities contained in a single ultra-low expansion glass (ULE) block [8].

Here we describe the frequency stabilization of different lasers radiations on the same optical cavity using the offset sideband locking technique that constitutes a simple, robust as well as transportable system which does not require a custom manufactured piece of equipment. The system is meant to serve the INRIM Yb optical lattice clock [9] to stabilize the lattice laser and the lasers for the two stage magneto optical trap (MOT) based on the $^1S_0 \rightarrow ^1P_1$, $\lambda=399$ nm, natural linewidth $\Gamma=29$ MHz and $^1S_0 \rightarrow ^3P_1$, $\lambda=556$ nm, $\Gamma=184$ kHz atomic transitions. The optical lattice operates at the so called magic wavelength (759 nm) where two atomic states of interest are perturbed by the same amount of ac Stark shift, resulting in an unperturbed clock transition [10]. The relative uncertainty related to the ac Stark shift has to be less than 1×10^{-18} . Given

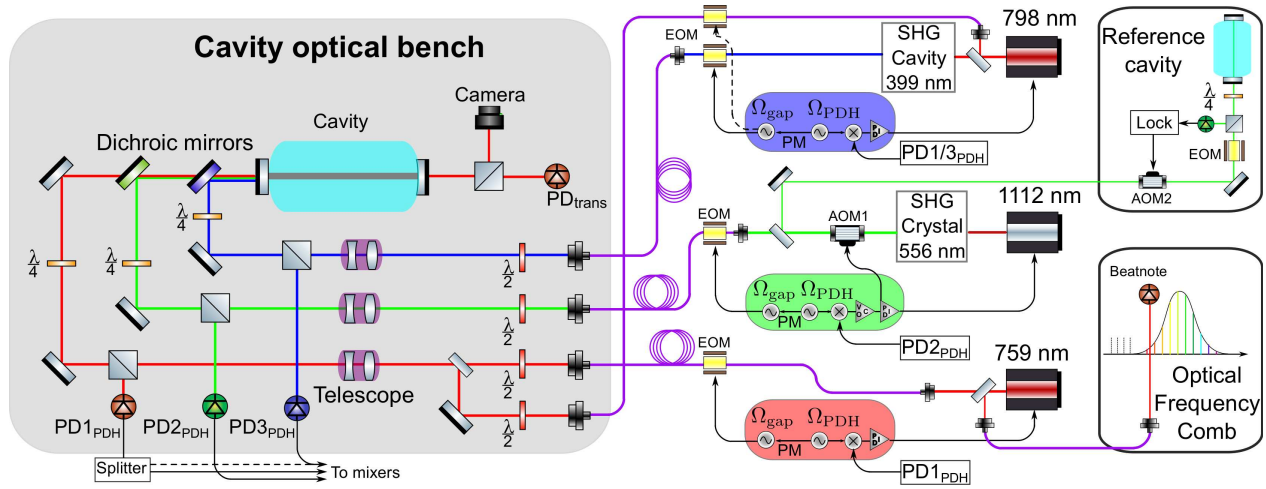


Fig. 1. Setup of the multi-wavelength cavity: black arrowed lines are electrical signal paths, dashed lines represent the electrical signal path for the 798 nm laser stabilization. Colored paths signify free-space laser light and polarizing maintaining fibers are in purple. In the right hand side of the picture the set up involving the reference cavity and the optical frequency comb are shown.

Table 1. Parameters used for locking the lasers. The bridge frequency for the 759 nm laser can be tuned to the preferred value according to the experimental conditions.

λ /nm	$P_{in}/\mu\text{W}$	Ω_{gap}/MHz	Ω_{PDH}/MHz
399	60.5	850.4	8.1
556	6.3	327.0	10.7
759	13.0	/	11.5
798	6.5	174.1	5.9

a first-order clock-transition sensitivity of $21.6 E_R \text{ mHz/GHz}$ [9] and lattice trap depth of 200 recoil energies (E_R), the total lattice frequency shift accumulated in a typical day of measure ($\approx 10 \text{ h}$) has to be smaller than 120 kHz. To operate the clock we require a laser linewidth and a daily drift less than 1 MHz at 399 nm and 100 kHz at 556 nm.

A drawing of the overall system is given in Fig. 1. The multi-wavelength cavity is made by Advanced Thin Films, it is a 10 cm ($\Delta\nu_{FSR} = 1.5 \text{ GHz}$) horizontal hemispherical resonator with cylindrical ULE spacer and fused silica mirrors kept inside a temperature-stabilized vacuum-housing. The mirrors are provided with ULE compensation-rings and the curved mirror has a radius of $R1 = -0.5 \text{ m}$. Both mirrors feature triple- ν coating for 399, 556 and 759 nm light. The manufacturer declared a finesse between 1000 and 3000 at 399 and 759 nm and higher than 15000 at 556 nm evaluated on coating design. The temperature of the vacuum housing is measured by a thermistor and is actively stabilized by a heater placed outside the vacuum below the cavity using the active disturbance rejection control method [11]. The vacuum housing is thermally isolated with foam and aluminum-foil while inside the vacuum we placed ten layers of crumpled Mylar foils. The 399 nm light is generated by cavity-enhanced second harmonic generation (SHG) from a tapered amplified diode laser at 798 nm [12] while the 556 nm radiation is produced by SHG of an amplified 1112 nm fiber laser in single pass through a non linear crystal. The lat-

tice beam is provided by a commercial titanium sapphire laser at 759 nm. Each laser beam passes through its respective EOM before reaching the cavity optical bench via polarization maintaining optical fibers. For the 798 nm, 759 and 556 nm lines, we used Jenoptik fiber-based broadband EOMs (up to $\sim 1 \text{ GHz}$) driven by commercial synthesizers capable of phase modulations with RF power of about 50 mW. For the 399 nm line we used a QBIG EOM with two resonance frequencies tunable in the ranges 0.6-1 GHz and 1-1.6 GHz (11 MHz PM bandwidth). This modulator is supplied by a custom made QBIG synthesizer which delivers the required 4 W RF power. The optical bench is a $60 \text{ cm} \times 90 \text{ cm} \times 1 \text{ cm}$ aluminum breadboard and, in addition to the cavity, accommodates the fiber output couplers, all the mode-matching telescopes as well as three photodiodes (PD_{PDH}) which detect the reflected light coming from the cavity. The cavity breadboard can be easily moved, ensuring transportability. Laser beams are superimposed on two dichroic mirrors before entering the cavity from the flat mirror side. The wavelengths are coupled to the cavity with high efficiency and the power of the light entering the cavity is reported in Tab. 1. A photodiode and a video camera, installed on the opposite side of the cavity entrance, monitor the transmitted light. The PDH frequencies (Ω_{PDH}) are set to different values and the electrical signals from the PD_{PDH} are filtered by narrow band-pass filters to avoid crosstalks. Furthermore, the 399 nm laser can be either stabilized directly to the cavity or using the 798 nm light. This laser beam is extracted before the duplication cavity and is sent, through an optical fiber, to the multi-wavelength cavity instead of the 399 nm light. On the cavity bench the beam is overlapped onto the 759 nm light on a 50/50 beamsplitter. The 798 nm and 759 nm light are then collected on the same photodiode (PD1_{PDH}) and the signal is splitted and separately filtered. After amplifications, the signals are down-converted to generate independent PDH error signals. The 399 nm (798 nm) and 556 nm bridging frequencies (Ω_{gap}) are set using the MOT as reference. In Tab. 1 are summarized the parameters used for locking all the different wavelengths.

The finesse was measured through cavity ring-down measurement, shutting down the EOM power while being locked on resonance and measuring the extinction of the transmitted light through the cavity with a fast photodiode. At 798 nm

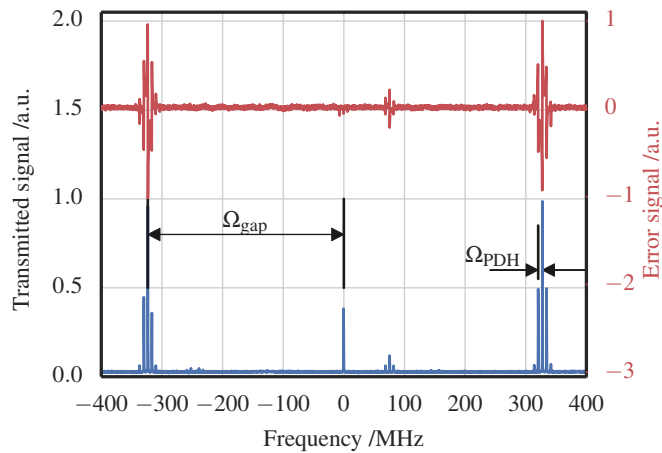


Fig. 2. Blue: Typical spectrum of the transmitted 559 nm light through the cavity. It shows the depleted carrier, the first order sidebands spaced by Ω_{gap} and the second order sidebands, generated by the PM signal, spaced by Ω_{PDH} . Smaller peaks are higher order cavity modes. Red: PDH error signal.

Table 2. Measured cavity properties.

λ/nm	Finesse		Throughput/%
	declared	measured	
399	1000-3000	550 ± 60	3
556	15 000	13900 ± 600	20
759	1000-3000	1660 ± 150	65
798	/	1200 ± 150	69

we obtained a finesse of 1200 ± 150 while the measured optical transmission (throughput) of the TEM_{00} mode through the cavity is 69% (see Tab.2). At 759 nm we have a finesse of 1670 ± 150 and a cavity mode transmission of 65%. At 556 nm we assessed a finesse of 13900 ± 600 and a transmission of 20%. At 399 nm the finesse is 550 ± 60 , it was measured using the linewidth of the transmitted TEM_{00} mode. The throughput is 3%, indicating high optical absorption at this wavelength.

The 556 nm laser is locked to the cavity with a fast lock utilizing an AOM (90 kHz control bandwidth) and a slow lock acting on the laser's piezo (3 kHz control bandwidth) using a proportional-integral-derivative (PID) control and a voltage-control oscillator (VCO). The frequency stabilization of the 399 nm/798 nm and 759 nm radiations acts only on the respective laser's piezo using a PID control with a control bandwidth of 3 kHz. According to the offset sideband locking technique we lock the frequency on a sideband generated by the EOM. Fig. 2 shows for example the PDH and transmitted signal for the 556 nm laser where the carrier is depleted in favor of the sidebands. The RF power sent to the EOM is adjusted maximizing the PDH error signal. The 399 nm laser remains locked typically about six hours and is limited by the doubling-cavity lock, whereas the stabilization of the 556 nm, 759 nm and 798 nm light operates for days without unlocks. One of the advantages of offset sideband locking is the possibility to change the carrier frequency while remaining locked. We have successfully

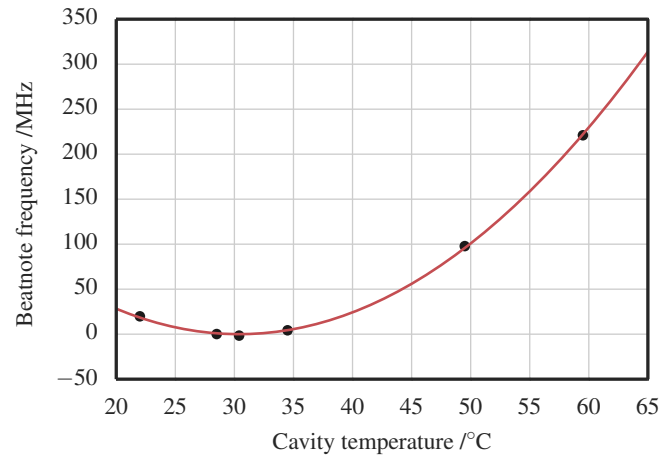


Fig. 3. Measurement of the zero CTE point by frequency-comparison of the two cavities at 556 nm.

observed this property by moving the carrier frequency as fast as 1 MHz/s up to 500 MHz span.

The temperature where the thermal expansion coefficient vanishes (zero CTE) was determined by measuring the frequency-difference between another cavity used as reference [13] and the multi-wavelength cavity while the temperature of the latter was changed. A separate branch of the stabilized 556 nm light is sent directly into the reference cavity and locked with a bandwidth of 100 kHz using a separate AOM (AOM2 in fig. 1). The frequency difference between the two cavities is measured directly as the frequency correction to AOM2. The result is shown in fig. 3, the zero CTE temperature is obtained from the minimum of the parabolic fit and is 30.4 ± 0.3 °C. These measurements were taken over the course of about one week, the reference cavity drift during this time is negligible. From the same signal we evaluated the frequency noise at 556 nm between the two cavities. From other measurements we estimate that this is dominated by the multi-wavelength cavity. We observed a linewidth, of less than 300 Hz by measuring the lock signal of AOM2 on the spectrum analyzer with 100 Hz of resolution and a sweep time of 80 ms (fig. 4). The frequency noise spectrum of the signal is reported in fig. 5, we assessed a white noise floor of $5 \text{ Hz}/\sqrt{\text{Hz}}$ and a flicker contribution of $15 \text{ Hz}/\sqrt{f}$ (f being the Fourier frequency). Typical acoustic noise is present between 10 Hz and 130 Hz. The measured fractional frequency stability at 1 s is 3×10^{-14} . To evaluate the cavity drift, we measured the frequency of the 759 nm laser locked to it using a fiber-based frequency comb referenced to an hydrogen maser. The light resonant with the cavity was sent to the frequency comb through an optical fiber. The beatnote of the laser and the comb tooth was detected using a fast photodiode. The signal is filtered, amplified and then counted using an electronic frequency counter. To highlight possible optical effects due to the simultaneous presence of different radiations inside the cavity, we measured the frequency drift of 759 nm light while the two other lasers (556 nm and 399 nm or 798 nm) are sequentially locked to the cavity. The result is shown in fig. 6, when the 556 nm, 759 nm and 798 nm lasers are simultaneously locked the observed drift is less than 2 kHz/h. However when the 399 nm light is locked to the cavity together with the 556 nm and 759 nm light, we observed an abrupt shift, about 50 kHz in 4 minutes (seen near the beginning of the trace) followed by a

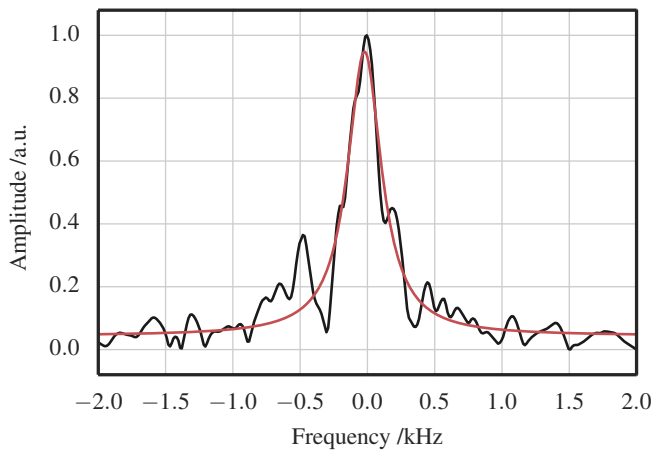


Fig. 4. Frequency spectrum of the 556 nm laser locked to the cavity and compared with the reference cavity.

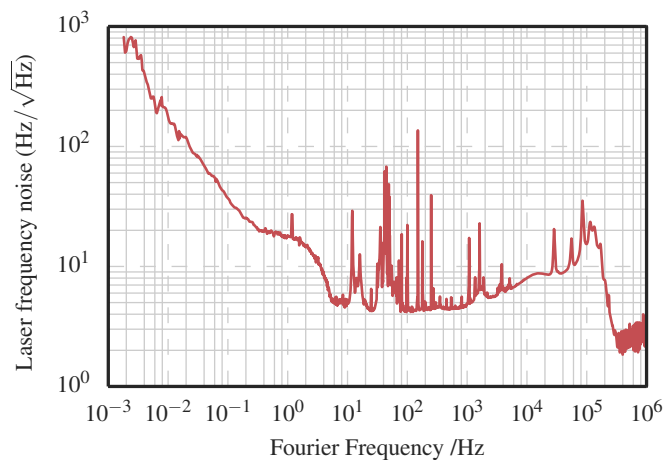


Fig. 5. Frequency noise spectrum of the 556 nm laser locked to the cavity.

steady 22 kHz/h drift. This effect comes from the high optical absorption (Tab. 2) of the coating toward the ultra-violet giving rise to thermal effects. Due to the resulting frequency drift of 220 kHz per day, higher than 120 kHz required, and the possible damage of the cavity optics on the long term, we decided to operate the system using the 798 nm light instead of the 399 nm.

In conclusion, we realized a frequency stabilization system for multiple lasers that satisfies the requirements given by the Yb optical lattice clock. Three different lasers are locked simultaneously to a single ULE-cavity using the offset sideband locking technique. This technique ensures extended frequency tunability for bridging the desired frequency gap. The most demanding stabilization, the 556 nm laser, exhibits a linewidth of 300 Hz and a stability of 3×10^{-14} at 1 s fulfilling the requirements for the clock operation. The best performances are obtained when the 798 nm laser is locked to the cavity (instead of the 399 nm light from SHG) giving a drift of less than 20 kHz in 10 h at 759 nm with all the lasers locked at the same time. This demonstrates the capabilities of the setup to ensure a lattice light shift uncertainty below 1×10^{-18} . The system has been tested locking simultaneously the 798 nm/399 nm, 556 nm and 759 nm lasers and operating the MOT during a typical working day without a measurable variation in number of atoms trapped in

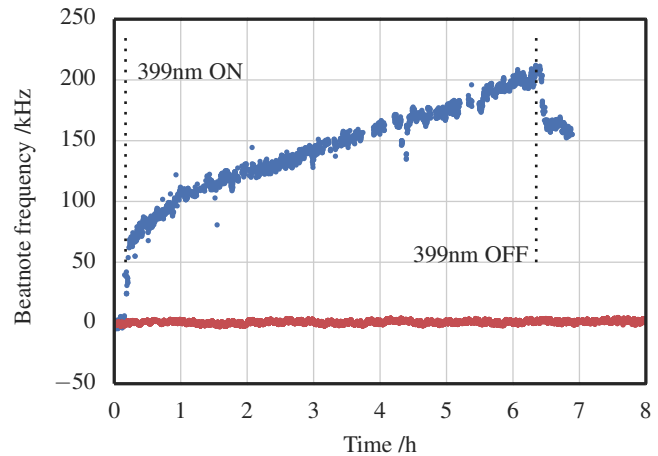


Fig. 6. Beatnote frequency of the 759 nm laser with the frequency comb referenced to an H-maser. Red: 798 nm 759 nm 556 nm lasers simultaneously locked to the cavity. Blue: 759 nm, 556 nm and 399 nm sequentially locked. Gaps in the data are cycle leaps of the counter.

the lattice. This system constitutes an easy, robust and compact solution for the simultaneous laser frequency stabilization for atom trapping as well as spectroscopic applications. This system could be improved by making it more compact using fiber combiner or by implementing a computer-controlled automatic drift compensation system.

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