

Optical phase locking of two extended-cavity diode lasers with ultra-low phase noise for atom interferometry

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Abstract We present a phase coherent laser system with ultra-low phase noise with a frequency difference of 6.9 GHz. The laser system consists of two extended-cavity diode lasers that are optically phase-locked with electrical feedback to the injection current of a slave laser. The bandwidth of the optical phase-locking loop is extended up to 8 MHz. We achieve the residual phase noise of two phase-locked lasers of below -120 dBrad²/Hz in the offset frequency range of 100 Hz–350 kHz and a flat phase noise of -127 dBrad²/Hz from 700 Hz to 20 kHz. These results are, to the best of our knowledge, the lowest phase noise level ever reported with two extended-cavity diode lasers.

1 Introduction

Two phase coherent lasers with a microwave frequency difference play an important role in atomic physics. In particular, for applications of coherent population trapping (CPT) [1], Raman velocity selection [2], Raman cooling [3], and atom interferometry [4], a pair of phase coherent lasers with a microwave frequency difference corresponding to the hyperfine splitting of ground states of alkali metal atoms are basic spectroscopic tools.

Specifically, for atom interferometry for the precise measurement of accelerations [4, 5], a pair of phase coherent lasers with low phase noise are essential for the interferometric sequence of atoms. In atom interferometry,

three pulses of counter-propagating laser beams are applied to the atoms to induce the stimulated Raman transitions between the two hyperfine ground states of atoms. The three pulses consist of $\pi/2 - \pi - \pi/2$ Raman pulses, which work as an atom splitter, mirror, and recombiner, respectively, by means of momentum transfer from photons of laser beams to atoms [4]. Through this process, the atoms are split into two parts and recombined after passing through the different paths. Since phase noise between two lasers is directly imprinted on the states of atoms during the stimulated Raman transitions, a pair of lasers with ultra-low phase noise are required to increase the sensitivity of the atom interferometer [6, 7].

One of the methods to produce a pair of phase coherent lasers is to use a modulation technique. The modulation can be applied to either the injection current of the laser directly [8, 9] or the carrier frequency of the laser with an electro-optic modulator (EOM) [10]. Modulation with an EOM is widely used for its simplicity, but EOM working at a few GHz range is very expensive and requires a large RF power to drive the EOM to produce a comparable sideband-to-carrier power ratio. In addition, unwanted sidebands, which are unavoidable in EOM modulation and not used in experiments, may cause systematic errors in particular experiments, especially in precision absolute atomic gravimetry [11]. The influence of parasitic sidebands should be properly evaluated [12]. Another method for making phase coherent lasers is using optically phase locking of two independent lasers with an electronic servo loop [13–16]. The optical phase locking is free from the unwanted sideband problem and has the advantage of being able to control the intensity and polarization of each laser independently. However, to reduce the residual phase noise of phase-locked lasers, the bandwidth of the electronic feedback servo needs to be widened [6] with enough loop

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gain. To reach a low phase noise level with a wide bandwidth [15], intra-cavity EOM [16] or a field-effect transistor (FET) feedback circuit has additionally been employed [15, 17].

Here, we construct an optical phase-locking loop (OPLL) with two extended-cavity diode lasers (ECDLs) with direct injection current control of the diode laser via bias tee. We are able to extend the bandwidth of the OPLL up to 8 MHz by tuning the phase lead compensation. As a result, the phase coherent laser system with a 6.9 GHz frequency offset achieves a residual phase noise level of -127 dBrad²/Hz in the offset frequency range of 700 Hz–20 kHz. Finally, we discuss the contribution of such a low phase noise OPLL laser system in enhancing the sensitivity limit of cold atom interferometry.

2 Experimental setup

Figure 1 shows a schematic diagram of the experimental setup for the OPLL of two ECDLs in constructing a Raman laser system. The external cavity of the ECDLs has a Littrow configuration. Commercial AR-coated laser diodes (Eagleyard Photonics EYP-RWE-810-03010-1300-SOT02-0000) are used for the ECDLs. The temperature of the base plate of the ECDL is stabilized within a few mK with active temperature control. The wavelength and the optical power from the ECDL are 780.1 nm and 20 mW, respectively. Part of the output from the master ECDL is sent to a saturated absorption spectrometer (SAS) to monitor its frequency. The frequency of the master ECDL is stabilized to the ⁸⁷Rb D2 transition from $F_g = 2$ to $F_c = 3$ with modulation transfer spectroscopy (MTS) [18]. The frequency of the slave ECDL is tuned to be near the transition from $F_g = 1$ to $F_c = 3$ by monitoring the SAS. The outputs of the two ECDLs are overlapped by a beam splitter and sent to the fast photodiode (Hamamatsu G4176-03) to detect the heterodyne beat signals of 6.9 GHz. The optical power of each laser that reaches the photodiode is 2 mW, which is near the maximum rating of the photodiode. Such a high optical power into the photodiode enables us to avoid using additional microwave amplifiers, which may degrade phase noise performance. And we do not use any frequency divider for heterodyne beat signal in order not to decrease phase error sensitivity. The power of the heterodyne beat signal is approximately -20 dBm with a 9-V bias for the photodiode. The beat signal of 6.9 GHz is down-converted to a low frequency of around 100 MHz by mixing with a low phase noise 7 GHz signal, which is synthesized using a 100 MHz frequency output from an ultra-low phase noise (ULN) quartz oscillator. For down-converting, a mixer (Marki M8-0412L) is used, and the 100 MHz ULN quartz oscillator is phase-locked to a

5 MHz ULN quartz oscillator. The down-converted 100 MHz beat signal is sent to a directional coupler (Mini-Circuits ZFDC-10-1) after being amplified by a low noise amplifier (Mini-Circuits ZFL-500LN). The output of the directional coupler is connected to an analog phase detector (Mini-Circuits ZRPD-1+) for phase detection. The coupled output of the directional coupler is used for monitoring the microwave spectrum and measuring the phase noise of the 100 MHz signal. The analog phase detector produces a phase error signal by comparing the phase of the down-converted beat signal with that of the 100 MHz signal from the ULN quartz oscillator. The phase error signal is divided into two paths for the slow and fast servo loops of the OPLL. For the fast servo loop, the phase error signal is connected directly to the injection current of the slave ECDL after it passes through a phase lead filter (PLF) and a bias tee (Mini-Circuits ZFBT-6GW+). The PLF is used to compensate the phase delay of the loop for the OPLL to have a much wider bandwidth. The PLF consists of a 180 Ω resistor and a 470 pF capacitor. The optimal values of the resistor and capacitor in the PLF are experimentally determined. The gain and the corner frequency of the P–I (proportional–integral) servo (Newport LB1005) are set to be optimal for the lowest phase noise level in the bandwidth. The total loop length of the OPLL, including the optical and microwave path length, is reduced as much as possible since a loop delay may produce an additional phase shift and limit the bandwidth of the OPLL. In our system, we keep the total loop length under 3 m, so that the loop delay can be maintained at less than 10 ns.

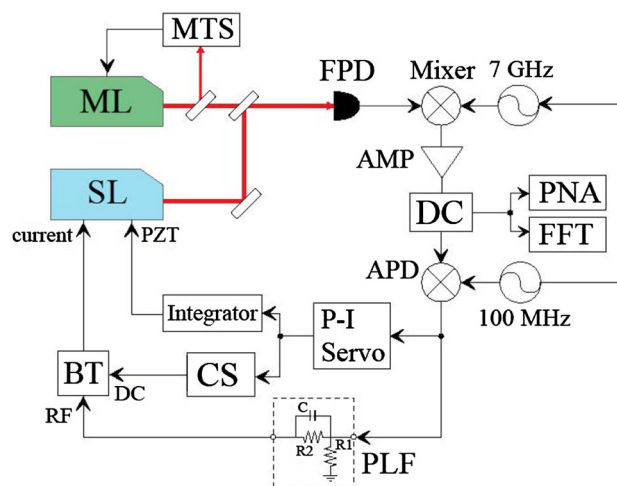


Fig. 1 Schematic diagram of the experimental setup for the OPLL of two ECDLs. *ML* master laser, *SL* slave laser, *MTS* modulation transfer spectroscopy, *FPD* fast photodiode, *AMP* amplifier, *DC* directional coupler, *APD* analog phase detector, *CS* current supply, *BT* bias tee, *PNA* phase noise analyzer, *FFT* fast Fourier transform analyzer, *PLF* phase lead filter ($R1$: 50 Ω , $R2$: 180 Ω , C : 470 pF)

For the P–I servo with a corner frequency of around 100 kHz, the phase error signal is fed to the current supply of the slave ECDL. The current from the current supply is injected through the DC port of a bias tee. The current supply is designed to have a wide bandwidth, a very low noise [19], and a P–I servo with a medium bandwidth and high gain. The P–I servo has a very high loop gain for the OPLL in a frequency range below a few hundreds kHz.

In order to keep the average output of the P–I servo zero, its output is integrated with a filter of a few 10 Hz bandwidth and fed to the piezoelectric transducer (PZT) attached to the diffraction grating of the slave ECDL. As this slow servo loop has infinite loop gain in the low frequency range, the long-term stability of the OPLL is enhanced and the long-term mode-hop-free operation of the ECDL is ensured.

In this experiment, we stabilize the frequency of the master ECDL to the ^{87}Rb D2 transition as mentioned above. However, for the application of the laser system to an atom interferometry, the frequency of the master ECDL is locked to another reference ECDL with a frequency offset because the laser frequencies should be far-detuned to the ^{87}Rb D2 transition to reduce the probability of one photon transition of atoms.

A phase noise analyzer (PNA) and a fast Fourier transform analyzer (FFT) are used to measure the phase noise of the beat signal.

3 Results and discussion

Figure 2 shows the spectrum of the phase-locked beat signal of 100 MHz measured with a microwave spectrum analyzer. The resolution bandwidth of the microwave spectrum analyzer is 1 kHz. The red line in Fig. 2 is the spectrum of the beat signal when two ECDLs are loosely locked with two independent servo loops of around 3 kHz bandwidth. The frequencies of two ECDLs are stabilized to the slopes of the atomic transition from $F_g = 1$ to $F_e = 2$ and from $F_g = 2$ to $F_e = 3$, respectively, using the SAS signals. The spectrum is well fitted with a Voigt profile, which is a line profile resulting from the convolution of a Gaussian and a Lorentzian profile. The Lorentzian linewidth and Gaussian linewidth of the beat signal are 20 kHz and 350 kHz, respectively, which is obtained by fitting the measured spectrum with a Voigt profile. This result shows the linewidths of the ECDLs used in the experiment.

The black line in Fig. 2 represents the measured beat spectrum when the phase-locking loop is working. The first side bump appears at the offset frequency of near 1.5 MHz, and it is mainly due to the bandwidth of the P–I servo, which has a high gain. The second side bump, caused by the bandwidth of the fast servo loop of the OPLL, appears

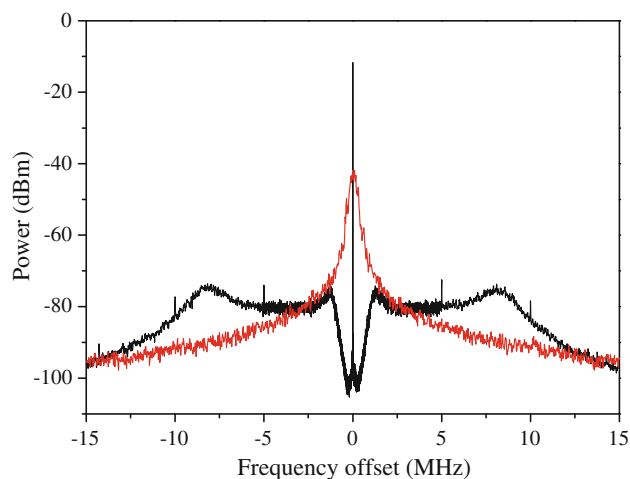


Fig. 2 Microwave spectrum of the down-converted output from the beating signal between two ECDLs. The red line and black line represent the spectrum with and without the phase-locking loop, respectively. The resolution bandwidth is 1 kHz

near 8 MHz. The bandwidth of the OPLL is wider than that of the typical OPLL obtained using the modulation of the injection current of the ECDL [13–15], and the bandwidth is comparable to that of the OPLL system achieved with an intra-cavity EOM [16].

In order to characterize the phase noise of the OPLL, we measure the residual phase noise of the power spectral density of the phase-locked beat signal with a FFT analyzer (Stanford Research Systems SR785) in the range of 1 Hz to 100 kHz. For this measurement, the phase of the output from the coupled port of the directional coupler in Fig. 1 is compared with the phase of a 100 MHz signal from the quartz oscillator. The measured phase noises are shown in Fig. 3. The phase noise at an offset frequency higher than 10 kHz is measured with a phase noise analyzer (Agilent E5052B). Although the phase noise analyzer can measure only absolute phase noise against the internal low noise reference oscillator of the analyzer, it is obvious from the measured results that the measurement system noise level is low enough to measure the residual phase noise of the OPLL in an offset frequency range higher than 10 kHz.

In Fig. 3, the phase noise reaches a flat floor of -127 dB rad^2/Hz in the offset frequency range of 700 Hz to 20 kHz and below -120 dB rad^2/Hz from 100 Hz to 350 kHz. This result shows that the residual phase noise of our laser system is lower than those of previous reports [6, 7, 13–17]. The phase variance $\langle \varphi^2 \rangle$ integrated from 1 Hz to 20 MHz is estimated to be 0.005 rad 2 .

The sensitivity of an atom interferometer can be evaluated from the measurement results when the OPLL laser system is applied to the atom interferometer. In a gravimeter, for example, the fractional measurement sensitivity is expressed as follows:

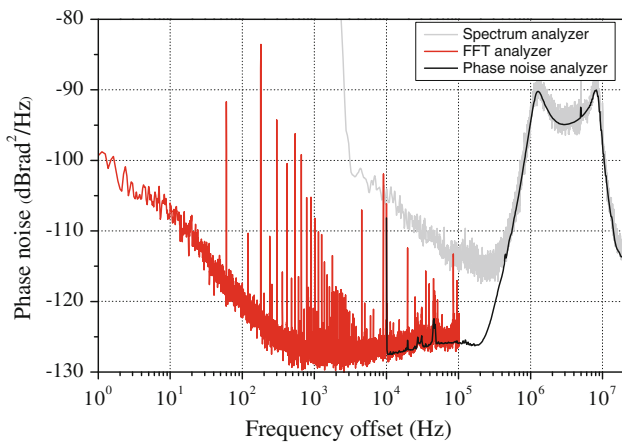


Fig. 3 Phase noise spectral density of the OPLL. From 1 Hz to 100 kHz, the phase noise is measured by a FFT analyzer. For an offset frequency between 10 kHz and 20 MHz, the phase noise is measured by a phase noise analyzer

$$\frac{\Delta g}{g} = \frac{\Delta\phi}{k_{\text{eff}}T^2g}, \tag{1}$$

where g is a gravitational acceleration, $\Delta\phi$ is the phase uncertainty [15], and k_{eff} is an effective wavenumber. Since the OPLL laser system works as Raman pulses that consist of one $\pi/2$ -pulse, one π -pulse, and another $\pi/2$ -pulse, k_{eff} is the sum of the wavenumbers of the Raman pulses. T is a time interval between two consecutive Raman pulses.

The phase uncertainty caused by the phase noise of the OPLL laser system is given by

$$\Delta\phi^2 = \int_0^\infty S_\phi(f)|H(2\pi f)|^2df, \tag{2}$$

where $S_\phi(f)$ is the power spectral density of the OPLL laser system and $|H(2\pi f)|^2$ is the weighting function which is given by

$$|H(2\pi f)|^2 = \left| -\frac{4\Omega\omega}{\omega^2 - \Omega^2} \sin\left(\omega\frac{T+2\tau}{2}\right) \left[\cos\left(\omega\frac{T+2\tau}{2}\right) + \frac{\Omega}{\omega} \sin\left(\omega\frac{T}{2}\right) \right] \right|^2 \tag{3}$$

where $\Omega = \pi/2\tau$ is Rabi frequency of the stimulated Raman transitions, τ is duration time of Raman pulses. The weighing function acts as a low-pass filter and has a cutoff frequency that is similar to the Rabi frequency of the Raman pulse interacting with an atomic wave packet [6, 7].

As we use the formalism of the weighting function in Eq. 3, we can estimate the phase uncertainty $\Delta\phi^2$ of our OPLL laser system and consequently the sensitivity limit $\Delta g/g$. The obtained sensitivity limit for different pulse lengths τ of Raman pulses is shown in Fig. 4. The time interval T is set at 150 ms. The sensitivity limits are similar to those of Ref. [15]

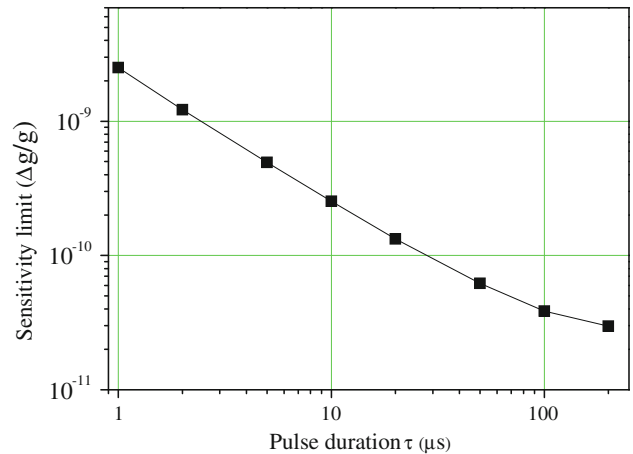


Fig. 4 Sensitivity limits given by OPLLs for different Raman pulse widths τ . $T = 150$ ms for standard operating parameter

in the pulse width range of 1–5 μs . However, the sensitivity limits of our OPLL laser system are lower than those of the laser system of Ref. [15] in a pulse width range longer than 5 μs . As the pulse duration increases, the difference between the two results becomes larger. This is because our OPLL laser system has lower phase noise characteristics in a high offset frequency up to 300 kHz than the results from Ref. [15]. In the case of $\tau = 100 \mu\text{s}$, for example, the sensitivity limit of our OPLL laser system is 4.0×10^{-10} which is five times lower than the previous report [15].

Our OPLL laser system shows better performance than the OPLL laser system that employs intra-cavity EOM [16]. The bandwidths of both OPLL laser systems are comparable. On the other hand, our system is more than two times better in terms of sensitivity limit for both cases of the pulse length $\tau = 1$ and 8 μs when the time interval $T = 100$ ms than the OPLL laser system that uses intra-cavity EOM.

4 Conclusion

We developed an ultra-low phase noise OPLL laser system with two ECDLs operating at 780 nm for cold atom interferometry. The bandwidth of the OPLL reaches up to 8 MHz, which is comparable to the bandwidth of the OPLL system that uses intra-cavity EOM [16]. We have achieved a residual phase noise of below -120 dBrad²/Hz in two phase-locked lasers in a frequency range of 100 Hz to 350 kHz and a flat phase noise of -127 dBrad²/Hz from 700 Hz to 20 kHz, which is, as far as we know, the lowest phase noise level ever reported with two ECDLs. We expect that this OPLL laser system will enable us to get a lower sensitivity limit when it is applied to the rubidium atom interferometry under development.

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References

1. R. Wynands, A. Nagel, *Appl. Phys. B* **68**, 1 (1999)
2. M. Kasevich, D.S. Weiss, E. Riis, K. Moler, S. Kasapi, S. Chu, *Phys. Rev. Lett.* **66**, 2297 (1991)
3. M. Kasevich, S. Chu, *Phys. Rev. Lett.* **69**, 1741 (1992)
4. M. Kasevich, S. Chu, *Phys. Rev. Lett.* **67**, 181 (1991)
5. S. Merlet, Q. Bodart, N. Malossi, A. Landragin, F. Pereira Dos Santos, O. Gitlein, L. Timmen, *Metrologia* **47**, L9 (2010)
6. J. Le Gouët, T.E. Mehlstäubler, J. Kim, S. Merlet, A. Clairon, A. Landragin, F. Pereira Dos Santos, *Appl. Phys. B* **92**, 133 (2008)
7. P. Cheinet, B. Canuel, F. Pereira Dos Santos, A. Gauguier, F. Yver-Leduc, A. Landragin, *IEEE Trans. Instrum. Meas.* **57**, 1141 (2008)
8. P.N. Melentiev, M.V. Subbotin, V.I. Balykin, *Laser Phys.* **11**, 891 (2001)
9. C.J. Myatt, N.R. Newbury, C.E. Wieman, *Opt. Lett.* **18**, 649 (1993)
10. V. Ménotet, R. Geiger, G. Stern, N. Zahzam, B. Battelier, A. Bresson, A. Landragin, P. Bouyer, *Opt. Lett.* **36**, 4128 (2011)
11. M. Weitz, B.C. Young, S. Chu, *Phys. Rev. A* **50**, 2438 (1994)
12. O. Carraz, R. Charrière, M. Cadoret, N. Zahzam, Y. Bidet, A. Bresson, *Phys. Rev. A* **86**, 033605 (2012)
13. G. Santarelli, A. Clairon, S.N. Lea, G.M. Tino, *Opt. Commun.* **104**, 339 (1994)
14. L. Cacciapuoti, M. de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M. Prevedelli, J. Stuhler, G.M. Tino, *Rev. Sci. Instrum.* **76**, 053111 (2005)
15. M. Schmidt, M. Prevedelli, A. Giorgini, G.M. Tino, A. Peters, *Appl. Phys. B* **102**, 11 (2011)
16. J. Le Gouët, J. Kim, C. Bourassin-Bouchet, M. Lours, A. Landragin, F. Pereira Dos Santos, *Opt. Commun.* **282**, 977 (2009)
17. J. Appel, A. MacRae, A.I. Lvovsky, *Meas. Sci. Technol.* **20**, 055302 (2009)
18. H.R. Noh, S.E. Park, L.Z. Li, J.-D. Park, C.-H. Cho, *Opt. Express* **19**, 23444 (2011)
19. K.G. Libbrecht, J.L. Hall, *Rev. Sci. Instrum.* **64**, 2133 (1993)