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Compensation of residual amplitude modulation fluctuations in an optoelectronic system for laser radiation frequency stabilisation

D.S. Kryuchkov, N.O. Zhadnov, K.S. Kudeyarov, G.A. Vishnyakova, K.Yu. Khabarova, N.N. Kolachevsky

Abstract. **Fluctuations of residual amplitude modulation in a scheme of laser frequency stabilisation by a Fabry–Perot cavity reduce the frequency stability of the laser systems intended for interrogating clock transitions of atoms and ions. The dependences of the residual amplitude modulation on a temperature of the waveguide-based electro-optical modulator used for modulating the radiation phase and on polarisation of the radiation are measured. The parameters are found, at which the influence of the residual amplitude modulation on the frequency stability is minimal. A system for active compensation is created, which reduces the contribution of fluctuations of residual amplitude modulation to the instability down to 2.1×10^{-16}, which makes it possible to reach the thermal noise limit of a silicon cryogenic cavity.**

Keywords: *ultrastable laser, Pound–Drever–Hall locking technique, residual amplitude modulation, electro-optical modulator, fractional frequency instability, Allan deviation.*

1. Introduction

Phase-modulation spectroscopy is known as the most accurate method for determining resonance centres of optical interferometers and spectral lines of atomic and molecular ensembles [1, 2]. Therefore, the phase-modulation methods are widely used in problems concerning optical clocks [3–5], in precision laser spectroscopy [6] and interferometry [7, 8].

Actually, as a rule, pure phase modulation of a laser radiation cannot be realised, because a residual amplitude modulation (RAM) inevitably arises as well [9, 10]. Particular attention should be paid to this effect while developing ultrastable lasers based on frequency locking to a mode of a highly stable cavity by the Pound–Drever–Hall locking technique (PDH) [2], taking into account that RAM occurs at a phase modulation frequency. Since RAM is demodulated concurrently with the desired signal that comprises information about the resonance position, the PDH error signal is shifted in amplitude to a certain value that depends on the amplitude modulation depth and phase. The best ultrastable laser systems reach a level of fractional frequency instability below 10^{-16} [11, 12]. This limitation is related to thermal noise [13] of reference cavity mirrors. Creation of laser systems with such stability requires extremely low intrinsic noise of optoelectronic systems used for forming laser radiation phase feedback. In some cases, the noise processes related to RAM become the principal factor that limitings the stability of laser frequency locked to the mode of the reference cavity.

An electro-optical modulator (EOM) is one of the elements widely used for modulating the laser radiation phase. RAM may arise due to the following reasons [14]:

1) a mismatch between the optical axis of the EOM crystal and polarisation direction of radiation;

2) effects of interferometers in an optical part of the PDH loop;

3) parasitic three-mirror interferometers including cavity mirrors and plane external faces of mirror substrates; and

4) temperature, piezoelectric, and photorefractive effects in the EOM crystal.

The first mechanism results in that the extraordinary polarisation component of laser radiation becomes modulated whereas the ordinary does not. In the result, the polarisation direction of radiation at the EOM output oscillates at the modulation frequency, which inevitably leads to amplitude modulation on passing through the next polarisation-sensitive element. This effect shifts the error signal by a constant value [14]

$$V_{\rm RAM} = \frac{1}{2}E_0^2 G \sin(2\alpha)\sin(2\beta)J_1(M)\sin(\Delta\varphi + \varphi_{\rm DC}), \qquad (1)$$

where E_0 is the electric field of laser radiation; G is the total gain of photodetection and demodulation processes; α and β are the angles between the EOM axis and input and output polarisers, respectively; J_1 is the first-order Bessel function; M is the difference of phase modulation indices for ordinary and extraordinary polarisations; $\Delta\varphi$ is the natural phase shift between ordinary and extraordinary polarisation components; and $\varphi_{\rm DC}$ is the phase shift due to a dc electric field.

Instability of the error signal may result from temperature-dependent low-Q parasitic interferometers (mechanisms 2 and 3) with the transmission and reflection coefficients slowly varying in time [14]. The effects caused by the interferometers arising between optical elements arranged prior to a

D.S. Kryuchkov, N.O. Zhadnov, K.S. Kudeyarov, G.A. Vishnyakova Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: kost1994@yandex.ru;
K.Yu. Khabarova Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; All-Russian Scientific-Research Institute of Physical-Technical and Radiotechnical Measurements, 141570 Mendeleevo, Moscow region, Russia;
N.N. Kolachevsky Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Russian Quantum Centre, Bol'shoi bul. 30, stroenie 1, 121205 Skolkovo, Moscow, Russia

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$\lambda/4$ plate in front of the cavity (see Fig. 1) can be detected and compensated for. RAM affected by interferometers arising between optical elements and the nearest cavity mirror or by three-mirror interferometers in the cavity can be detected only jointly with a PDH signal and inevitably contributes to the instability of the latter. Some interferometers in the optical scheme can be eliminated by arranging the optical elements at a small angle to the beam axis, depositing antireflection coatings, and using optical isolators [15]. In turn, three-mirror interferometers including cavity mirrors are conventionally rather stable because these mirrors have a low thermal expansion coefficient, are temperature-stabilised and mechanically stable.

Varying properties of a nonlinear medium under the action of changing crystal temperature or radio-frequency/laser fields (mechanism 4) cause a drift of the RAM depth produced by EOM. It was shown [14] that in the case of passive temperature stabilisation, the best nonlinear crystal is KDP (KH_2PO_4). In the case of active stabilisation loop, RAM instability is determined by influence of parasitic interferometers and will be the same for the most of crystals.

A classical method for compensating RAM fluctuations is a combined feedback loop with controlled dc voltage applied to EOM and its temperature [15, 16]. The amplitude modulation is detected in the place of optical scheme nearest to the cavity. The main part of RAM noise power is concentrated in a spectrum range below 100 Hz [15]; therefore, requirements to the feedback bandwidth are not strong.

This method provides stabilisation of the RAM depth with the absolute accuracy of up to 10^{-6} and makes it possible to create laser systems with a frequency instability of 3×10^{-17} [11]. An alternate method for compensating RAM from EOM is summing signals obtained from photodiodes, which detect the radiation reflected from polarisation splitter in front of the cavity and radiation reflected from the cavity [17]. It is a simple method; however, effects of some parasitic interferometers may escape the control. The value of RAM can be substantially reduced by the following: the employment of EOM with weedged crystal facets [18], which separates ordinary and extraordinary beams spatially; accurate choice of crystal temperature and the position of the laser beam on the crystal [16]; in some schemes, the employment of Faraday rotators instead of the optical isolators, which can form parasitic interferometers themselves [19].

2. Experimental setup

Laboratory of Optics of Complex Quantum Systems at the Lebedev Physical Institute works on creation of ultrastable laser systems based on high-Q silicon cavities in filled cryostats of original design [13, 20, 21]. Fabry–Perot cavities from single-crystal silicon have a low level of thermal noise, which opens a possibility to develop a laser with a fractional frequency instability limit of 2×10^{-16} using mirrors with SiO_2/Ta_2O_5 dielectric coatings. RAM fluctuations may hinder reaching so low instability, which necessitates creation of the system for detecting and compensating this effect.

Figure 1 presents the scheme for RAM detection and stabilisation, which has been incorporated in our system that stabilises the radiation frequency of a Koheras AdjustIK E15 fibre laser at a wavelength of 1542 nm by the Pound–Drever–Hall locking technique [22]. The radiation phase was modulated by a waveguide-based electro-optical modulator on a $LiNbO_3$ crystal with polarisation-maintaining fibre

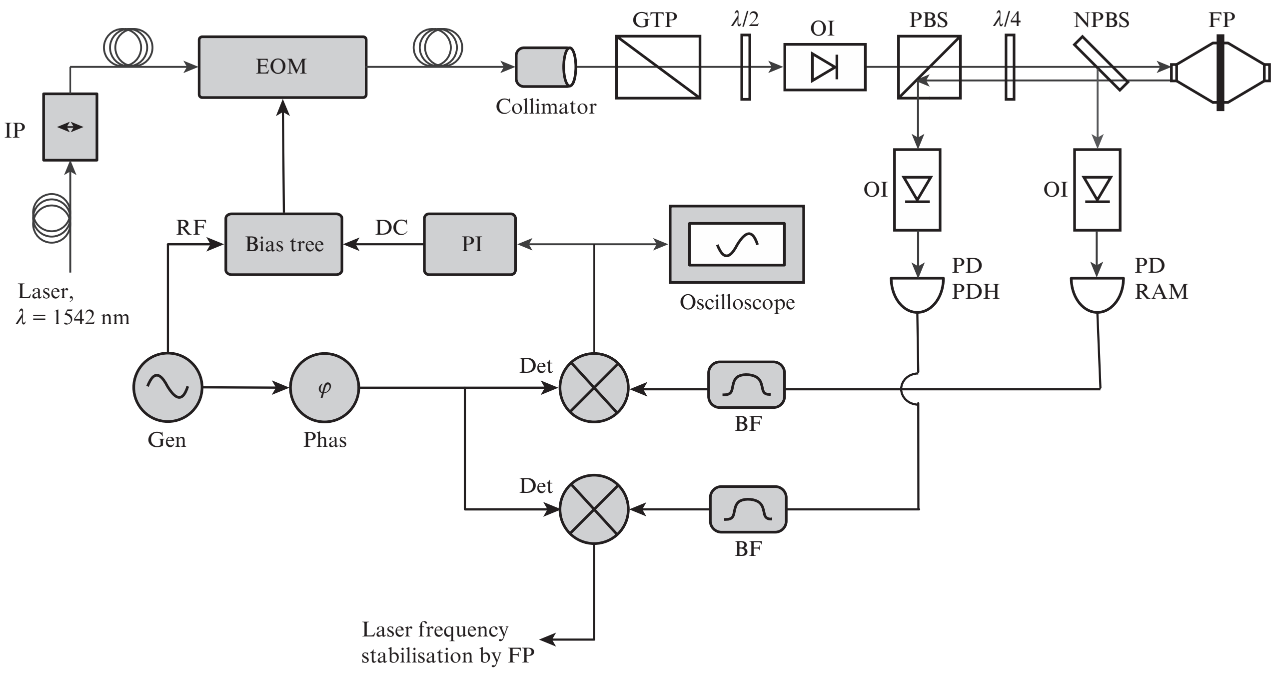

Figure 1. RAM detection and stabilisation schemes:
(IP) in-line polariser; (EOM) electro-optical modulator; (GTP) Glan–Taylor prism; ($\lambda/2$) half-wave plate; ($\lambda/4$) quarter-wave plate; (OI) optical isolator; (PBS) polarising beam splitter; (NPBS) non-polarising beam splitter; (FP) Fabry–Perot cavity; (PD PDH) photodetector used in the Pound–Drever–Hall locking technique for laser frequency stabilisation; (PD RAM) photodetector used for detection of residual amplitude modulation; (BF) bandpass filter; (Det) phase detector; (PI) proportional-integral amplifier; (Phas) phase shifter; (Gen) radiofrequency generator; (RF) radio-frequency input; (DC) low-frequency input.

leads (iXblue MPX-LN-0.1). On the one hand, imperfect matching of the crystal and fibre lead axes inevitably results in the emergence of RAM with the depth fluctuating due to environment influence on EOM. However, the half-wave voltage (that is, the voltage needed for shifting the radiation phase by π) of the modulator employed is only 3.5 V, which is by two orders of magnitude less than the half-wave voltage of free-space EOM and, thus, simplifies the system of active compensation of RAM fluctuations. In addition, waveguide EOM provides a homogeneous modulation over the entire cross section of a light beam.

A modulation signal at a frequency of 29 MHz is sent to EOM from a Stanford Research Systems DS345 generator (Gen) through a Mini-Circuits SFBT-4R2GW-FT+ bias tree, which provides summing a radiofrequency signal with dc voltage for realising active stabilisation of the RAM. Polarisation of the radiation introduced to the modulator is determined by a fibre in-line polariser (IP). A Glan–Taylor prism (GTP) used as an output polariser provides a high polarisation extinction ratio (100000 : 1). Then the radiation is reflected from the Fabry–Perot cavity (FP) and passes to a photodetector (PDH PD), whose signal is used for stabilising the laser radiation frequency. The signal from PDH PD cannot be used for independent detection of RAM simultaneously with the laser frequency stabilisation. Therefore, prior to passing into the vacuum chamber of the cavity, part of the radiation is split by a non-polarising beam splitter (NPBS) (a plate with a dielectric coating reflecting approximately 50% of radiation falling at an angle of 45°; the reflection coefficients for s- and p-polarisations differ by at most ~30%) and passes to an additional photodetector (RAM PD). For eliminating parasitic interferometers, all optical elements are slightly inclined with respect to the laser beam axis. In addition, optical isolators (OIs) with the degree of isolation 35 dB are placed after the output polariser and in front of both the photodetectors.

For detecting and compensating RAM fluctuations, the RAM signal from RAM PD at a frequency of 29 MHz having passed a bandpass filter (BF) is demodulated by mixing with a reference signal from the generator on the phase detector (Det). To make the signal from RAM PD the closest 'copy' of the RAM signal on PDH PD, two identical electronic schemes are used after both the photodetectors and equal phases of reference signals are set by a phase shifter (Phas). After demodulation, the signal is controlled by an oscilloscope and can be used for active compensation of RAM.

3. Study and stabilisation of residual amplitude modulation

For determining the parameters that minimise the influence of RAM on the laser system radiation frequency, the amplitude modulation depth was studied as a function of the rotation angle of the output polariser and the temperature of the electro-optical modulator. The temperature dependence of RAM is determined by the factor $\sin(\Delta\varphi + \varphi_{DC})$ in formula (1), where the parameter $\Delta\varphi$ is determined by temperature-dependent characteristics of crystal birefringence. The EOM temperature is controlled by a thermistor with a negative temperature coefficient and nominal resistance of 10 kΩ and stabilised by the resistive heater, which is controlled by a proportional-integral controller. During the study of the temperature dependence the fixed rotation angle of the output polariser was fixed at $\beta = 5°$ (with respect to the angle corresponding to the minimal RAM signal) and the temperature was stabilised at a desired point, which was checked by the damping of signal fluctuations. At certain instants, residual signal oscillations were observed with the amplitude of up to 60 mV, which were not correlated with the temperature stabilisation process and might be related to varying laboratory temperature that affected parasitic interferometers. For comparison, the error signal of the laser radiation stabilising feedback in the Pound–Drever–Hall scheme is 0.5 V. The dependence measured (Fig. 2) was approximated by a harmonic function with a period of 0.8 K, which corresponds to a temperature sensitivity of 7.85(3) rad K^{-1}. Note that in the case of passive stabilisation of the RAM signal, the temperature should be stabilised near the top of sinusoid where sensitivity to temperature fluctuations is minimal. In turn, an active compensation that will be described below requires a EOM temperature stabilisation point at the slope of the curve in Fig. 2.

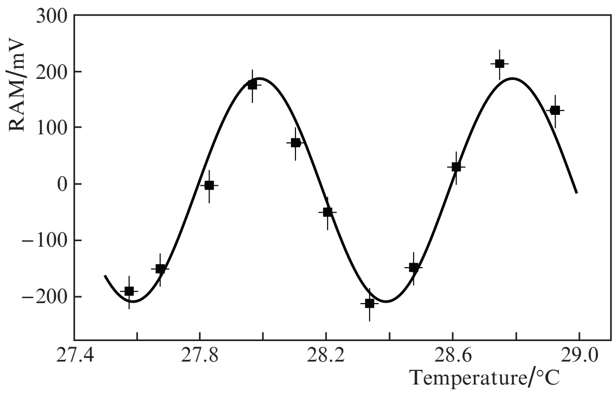

Figure 2. RAM level vs. temperature of electro-optical modulator at constant angle of output polariser $\beta = 5°$.

A dependence of the RAM signal on the rotation angle of the Glan–Taylor prism is shown in Fig. 3. To exclude the influence of temperature effects, the EOM temperature was scanned in the range of 27.5–29 °C at each rotation angle. The value of the RAM signal was detected at four various extrema and then it was averaged. The dependence of the rotation angle of output polariser β is described, according to (1), by the factor $\sin(2\beta)$. The scheme of our experiment introduces an additional factor $\cos^2(\gamma - \beta)$, where γ is the angle between the polarisation direction of light passed from EOM and the axis of an optical isolator, on which the polarisation vector of light after Glan–Taylor prism is projected. Measurement results were approximated by the dependence $A + B\sin(2\beta)\cos^2(\gamma - \beta)$ with the parameters $A = -11(6)$ mV, $B = 5.1(8)$ V, $\gamma = 12(1)°$. The present study allows one to determine the position of zero angle β on the polariser scale, which corresponds to the minimal level of residual amplitude modulation. Nevertheless, even setting the exact zero-angle position does not eliminate an influence of fluctuations because temperature and acoustic impacts on fibre parts of the input polariser and EOM change the polarisation of passed light, which results in an effective change in the rotation angle of the output polariser.

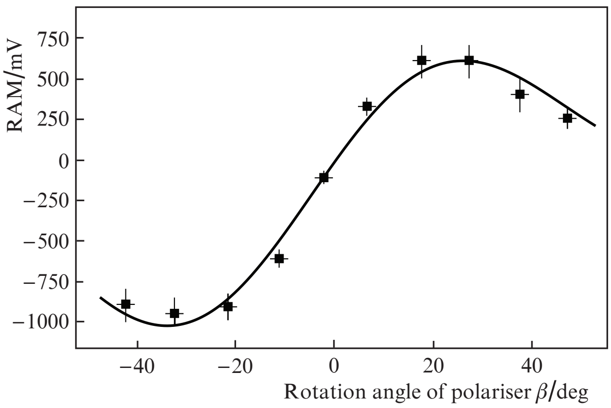

Figure 3. RAM level vs. rotation angle β of output polariser.

For studying the contribution of RAM fluctuations to the frequency instability of the laser light, the time dependence of the fluctuations was recorded by an oscilloscope and then analysed in terms of Allan deviation [23]. In order to transfer from the instability of a RAM signal measured in volts to the radiation frequency instability in hertz we have measured the corresponding sensitivity. For this purpose, a beat signal of two identical laser systems was used. Simultaneously with the beat frequency measurement, a RAM signal from one of the systems was modulated by applying a sinusoidal signal with the amplitude of 4 V and frequency of 1 Hz to the DC input of the bias tree. The corresponding dependences of RAM and the beat frequency on time are presented in Fig. 4. An average value of frequency variation under the action of modulation yielded the sensitivity of 0.9(1) Hz mV^{-1}.

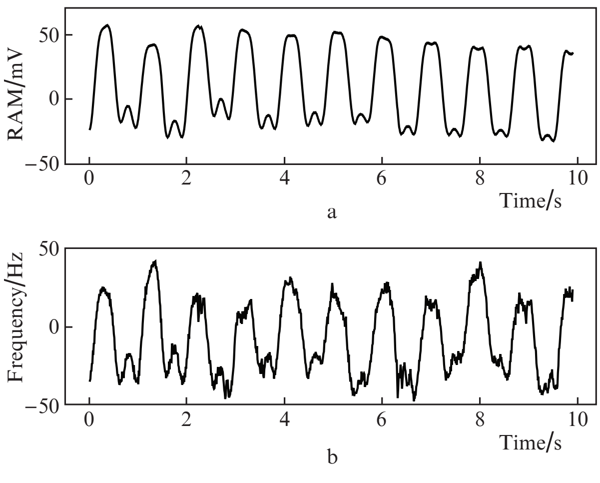

Figure 4. (a) RAM as a function of time in the case of a sinusoidal signal with an amplitude of 4 V and frequency of 1 Hz applied to the bias tree DC input and (b) change in the beat frequency of two laser systems under the action of RAM modulation.

Taking into account the sensitivity obtained, the fractional instability of laser radiation frequency due to RAM fluctuations in the conditions of our experiment was 2.5×10^{-15} at the averaging time of 0.01 s and reaches 5×10^{-14} at averaging time 1 – 10 s (Fig.5). Thus, RAM noise prevents reaching the thermal noise limit of cryogenic silicon cavity.

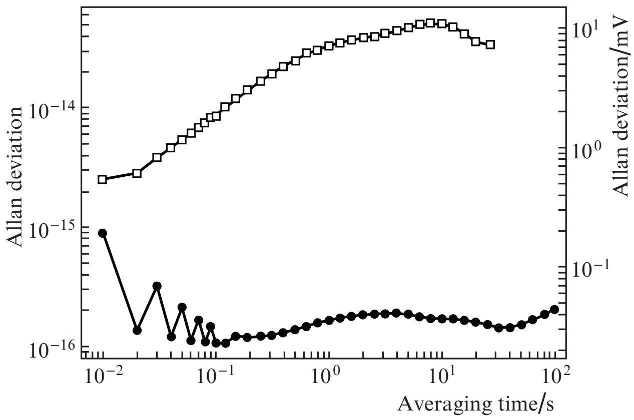

Figure 5. RAM instability (right scale) and its contribution to laser fractional frequency instability (left scale) without active stabilisation (□) and with the active stabilisation loop switched on (●).

To prevent the influence of RAM fluctuations on the radiation frequency, an active compensation system has been realised (see Fig. 1). A demodulated RAM signal passed to a proportional-integral amplifier (PI) for forming the error signal. Through the DC input of the bias tree, the error signal passed to the EOM and stabilised the RAM signal changing the phase φ_{DC} (see Fig. 1). A change in the dc voltage applied to the EOM crystal is equivalent to a change of its temperature; therefore, the operation point for stabilisation can be chosen at a slope of the temperature dependence (for example, at 28.6 °C in our system). One should also remember that the factor dependent on the polariser rotation angle determines the range of possible RAM variations through constant voltage and temperature. This range should be sufficient for compensating observed RAM fluctuations; therefore, for expanding it, the output polariser was rotated to an angle of about 1° from the optimal position, which corresponded to the range of RAM variations of about 80 mV. For using the entire range, it is necessary to have the possibility of varying the dc voltage applied to EOM up to the half-wave voltage. The employment of the active compensation system allowed us to reach the RAM instability of 4×10^{-2} mV (which corresponds to the absolute instability of the amplitude modulation depth of 6×10^{-6}). A contribution of RAM fluctuations into the laser frequency instability at such averaging time does not exceed 2.1×10^{-16} (Fig. 5). The specific view of the instability at short times is explained by a pickup from 50-Hz alternating-current mains. The latter factor may be eliminated by improving the electric scheme.

4. Conclusions

Study of temperature and polarisation dependences of RAM makes it possible to determine the system parameters needed for compensating RAM fluctuations. In some cases, a passive stabilisation may be sufficient for increasing stability of the laser system based on a high-Q Fabry – Perot cavity. However, systems with low thermal noise, such as silicon cryogenic cavities, require an active stabilisation system. The compensation system realised in the present work allows one to reduce the RAM contribution down to 2.1×10^{-16} at the averaging time of 0.1 – 100 s, which suffices for a wide range of problems in precision spectroscopy and metrology.

Note that operation of the active compensation system was accompanied with a slow drift of the error signal range from a slope of sinusoid to its maximum, which, in our opinion, can be explained by temperature fluctuations in laboratory that affect parasitic interferometers or electronic components. This problem can be solved by using active adjustment of EOM temperature. This approach will be realised in the future for more reliable stabilisation of laser radiation frequency at a long averaging time.

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