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Stabilization of diode-laser frequency to atomic transitions

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Different methods of stabilization of diode lasers are reviewed with the emphasis on stabilization to atomic transitions. The stabilization methods to Doppler-broadened and Doppler-free resonances are presented. A novel method of stabilization using the saturated dichroism of atomic vapours is described. An example of stability transfer from the diode laser onto the reference Fabry–Perot cavity is presented.

Keywords: laser stabilization, dichroism.

1. Introduction

Laser diodes have become in recent years the most frequently used type of laser. The widespread use of diode lasers within telecommunication applications and its mass production led to its popularity also in the scientific community. They are frequently used in different spectroscopic experiments due to their simple construction and, especially, ease of power control and wavelength tuning [1]. The laser diodes are operating in a single transverse and longitudinal mode which limits the power to a few tens of miliwatts (in the visible and close infrared ranges), but this level of intensity is quite sufficient for the majority of spectroscopic applications. The geometrical characteristics of the laser-diode beams are not perfect, but the drawbacks (elliptical beam shape, astigmatism) may, if necessary, be corrected by a properly constructed optical system, and even if not corrected, do not impose serious difficulties.

The frequency of a laser diode is not perfectly stable. As in any other kind of a laser this frequency instability is connected with the shifts of the gain profile and with the changes of the optical length of a resonator caused by the different environmental parameters. Without pretending to present a complete list let us name here the mechanical vibrations, variations of temperature, air pressure, and any physical parameter that leads to changes of the refractive index of the medium inside the resonator. These changes are sometimes divided based on their time scale into the long -term drifts and short-term fluctuations. As a specific example let us consider the

AlGaAs diode laser around the 800 nm wavelength. The temperature changes cause a double effect: the thermal dependence of the refractive index of the semiconductor crystal tunes the laser mode frequency by 0.06 nm/K while the temperature modification of the bandgap shifts the gain profile 0.25 nm/K. The discrepancy between the two tuning slopes causes jumps between the resonator modes. The changes in the diode current modify the carrier density which influences the refractive index and results in the current tuning of about 3 GHz/mA (0.006 nm/mA).

In many applications the possibility of precise control of the laser frequency and of its stabilization is of critical importance. This is so in the telecommunication uses, where the requirement of the high throughput of an optical fibre is fulfilled by the wavelength-division multiplexing (WDM) technique. The evolution of this method goes in the direction of multiplying the number of the wavelength channels, which, together with the limitation caused by the width of the transmission window of the fibre, make it necessary to decrease the wavelength/frequency distance between the neighbouring channels. The present directive of the ITU defines the channel separation in the dense WDM (DWDM) as 100, 50, 25 or even 12.5 GHz [2]. This requires a precise control of the laser frequency to stay very close to the defined frequency grid and call for good frequency references: diode lasers stabilized to the acetylene absorption lines close to $\lambda = 1500$ nm, or lasers stabilized to Rb lines used as two-photon standards [3]. Similar requirement regarding the stability of the laser wavelength applies to other applications, where we name only some examples.

Analytical spectroscopy and trace element detection as applied to the pollution monitoring or detection of drugs or explosives, also the detectors used in the production of ultra-pure materials, they all require the exact tuning of the laser frequency to the atomic or molecular line, *i.e.*, the laser frequency stability must comply with the line width of single GHz. In the case of the biosensors the spectral features are broader, but the accuracy and repeatability requirements call for high laser frequency stability. Caesium and rubidium atomic clocks using the techniques of optical excitation and detection, also the space-borne atomic clocks [4], [5] are the applications where the highest possible stability is of prime importance.

Another class of applications are the ones where only the laser wavelength stability is important, without the specification of its precise value. These are the laser interferometers and positioning systems, laser gyro detectors, holography.

2. Passive methods

As the diode-laser frequency (and power) depends sensitively on the temperature of the diode and on the injection current, it is important to use a current source and temperature controller of good stability and low noise. The example laser parameters given above can be used to estimate the required stability in temperature and current. In practice the temperature stability should be of the order of 1 mK and current stabilized down to single μA, and even with these values the laser stability is not perfect.

3. Stabilization to external resonators

The specific features of the diode lasers: high gain and low reflection coefficient of the crystal facets serving as the laser resonator mirrors cause that such lasers are highly sensitive to the external optical feedback and even small amounts of feedback (injection power as low as 10^{-5} of the output power) may strongly influence the emission characteristics. It is therefore easy to couple the diode laser to an external optical resonator. A logical step towards the miniaturisation of such lasers is placing a spatially periodic section within the semiconductor structure, so that the laser emission wavelength is set by such a grating. There are two kinds of such diodes: distributed feedback (DFB), where the active area is periodically modulated and distributed Bragg reflector (DBR), where the modulated section is separated from the active area and acts as a selective reflector. Such diode lasers allow the wavelength to be tuned in a small range by changing the refractive index of the grating caused by the temperature and/or current modification.

A much higher freedom in the wavelength tuning is offered by lasers with an external optical resonator. For a review of the possible configurations see paper [1]. The resonators have most often a diffraction grating as a dispersive element, while precise selection of the laser frequency is done by tuning the resonator length by a piezoelectric actuator. Such a laser resonator can host different laser diodes, so the overall wavelength span can be very broad. On the other hand, it should be stabilized to an independent reference. Such a role may be played by a confocal Fabry–Perot resonator [6] and then the absolute stability of the emitted radiation will depend on the mechanical and thermal stability of the reference.

The confocal Fabry–Perot interferometer is commonly used as a frequency reference since it possesses several positive characteristics: it is easy to couple the light in and out, with the high reflectivity mirrors the interference fringes are very narrow (interferometer has high finesse) and form a regular, equidistant grid of transmission maxima in the frequency domain.

A general feedback scheme is presented in Fig. 1. In the simplest configuration, the laser frequency is tuned to the side of the Lorentzian-shaped fringe as shown in the inset. The difference between the transmission signal and some reference voltage gives a convenient error signal: close to half of the maximum transmission the difference signal reacts almost linearly to the frequency deviations and the sign of the error signal may by reversed by tuning the laser to the opposite slope. Such a stabilization scheme requires no modulation of the laser frequency, but is prone to errors caused by the laser intensity instabilities, which are interpreted as frequency shifts. To avoid such crosstalks, additional channel measuring the laser intensity is required or the modulation method can be applied. In this scheme (presented in Fig. 2), a slight modulation of the laser frequency is introduced and the electronic phase sensitive detection (lock-in) of the modulated part of the transmission signal is used. The lock-in produces a derivative of the transmission signal which is a dispersive -shaped antisymmetric curve playing the role of the error signal. The laser frequency

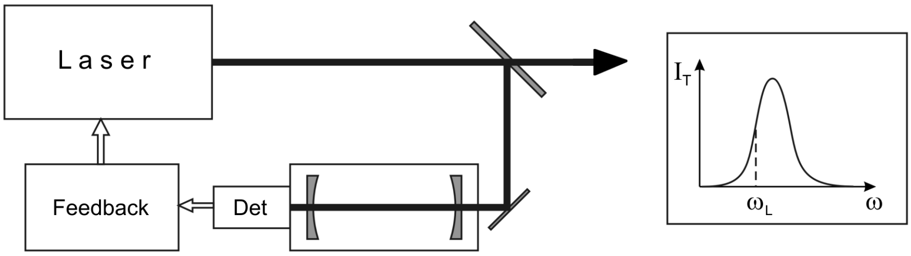

Fig. 1. Side-of-fringe stabilization scheme of the laser frequency to the external Fabry–Perot cavity.

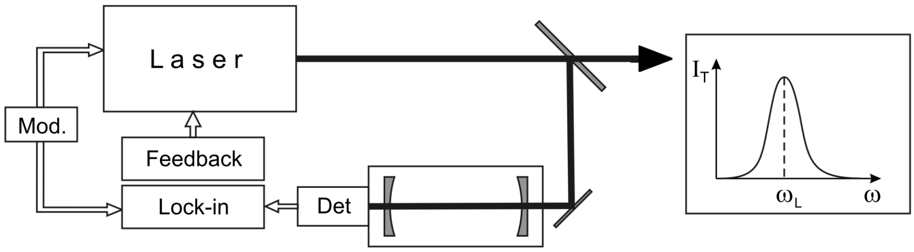

Fig. 2. Center-of-fringe stabilization scheme of the laser frequency to the external Fabry–Perot cavity.

is stabilized to the zero-crossing point of the derivative curve, *i.e.*, to the centre of the fringe. The modulation method is free from errors caused by the intensity modulation.

In any stabilization scheme to the Fabry–Perot cavity the resonator eigenfrequencies may be easily tuned by a piezo-driven mirror or internal galvo-rotated glass plate, so that any laser frequency may be stabilized to such a reference. On the other hand, the reference stability is dictated by the mechanical and thermal stability of the interferometer. Therefore, for high precision measurements the interferometer must be placed in a temperature stabilized environment, often in an evacuated container and should be effectively decoupled from the laboratory acoustic noise sources, which necessitates elaborated systems of suspension and isolation. This obviously adds to the cost and complication of the stabilization system. An alternative method is to stabilize the laser to an atomic transition reference.

4. Stabilization to atomic transitions

Atomic spectra are the physical references upon which the contemporary definitions of time (second) and length (meter) units are based. Stabilization of laser frequency to atomic transitions offers a series of advantages:

– repeatability of the laser frequency setting due to the absolute stability of the atomic reference;

– accuracy of the frequency stability due to a narrow linewidth of the atomic transition;

– possibility of locking the different lasers to different atomic transitions – freedom of selecting the reference wavelength in different spectral domains.

Although any atomic spectrum is composed of a limited set of transition frequencies and not all of them may serve as a convenient reference, the limitation on the laser frequency is not that severe. The laser frequency need not be exactly at the atomic reference. The stabilization scheme may compare the laser frequency shifted by a suitable modulator to the atomic reference and thus the stabilized frequency is shifted from the atomic frequency by the modulation frequency. Another possibility is the, so-called, "offset lock" scheme, where the beam from one master laser stabilized to the atomic reference is mixed with the beam from another laser and the beat frequency is detected and stabilized. With the advances in the rf electronics such schemes become possible for ever higher difference frequencies with extreme accuracy. Yet another possibility is to use the transitions in molecules as references and there are rich molecular spectra which are well tabularised [7]–[9].

The existing methods of stabilization may be divided into two general classes: the ones using atomic transitions broadened by the Doppler effect and the others, using Doppler-free resonances. In the first case the linewidth of an atomic line is of the order of a GHz, in the second case it is of the order of single MHz, or even less. The very narrow lines, used as primary frequency standards, pose additional difficulties, so they are not used for laser stabilization. Stabilization methods based on Doppler-broadened transitions offer broad capture range, but lower frequency precision. Sub-Doppler methods use non-linear optical processes to select only a single class of atoms with one velocity; they offer higher frequency accuracy with lower capture range.

4.1. Doppler-broadened resonances

The stabilization of a laser frequency to a Doppler-broadened atomic transition is a simple extension of any method of laser spectroscopy. Let us mention here that different detection methods may be used: by far the most popular is the laser beam absorption, but the optogalvanic detection offers the advantage of direct conversion of optical signal into an electric one without any photodetector and is useful for different elements with low vapour pressure. The photoacoustic method can be used for samples of higher pressure. Other optical methods, like the ones based on the polarization in dichroism measurements are also possible and will be discussed below.

4.2. Doppler-free resonances

The most popular Doppler-free method used for laser stabilization is the saturated absorption method. In the simplest realization it uses two counter-propagating laser beams of the same frequency, but with different intensities. The strong laser beam excites atoms of a velocity class that corresponds to the frequency difference $\omega - \omega_0$, between the laser beam and atomic transition and thus modifies the velocity distribution in the ground and excited state (see Fig. 3). The counter-propagating weak beam probes the absorption of such a medium. If the frequency difference is not zero, the two beams interact with different velocity classes and the probe beam absorption

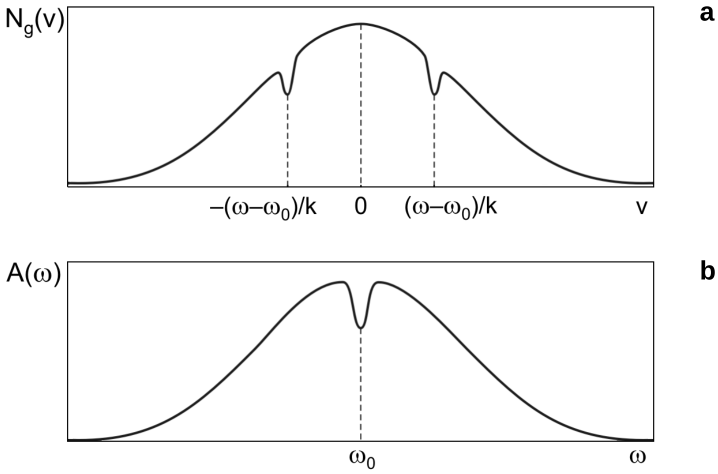

Fig. 3. Principle of the saturated absorption spectroscopy method: the velocity distribution of atoms in the lower level with two holes burned by the pump and probe laser beams of frequency ω and equal intensities (**a**), and the probe absorption *vs*. laser frequency with a decreased absorption for the exact resonance (**b**). Usually, the probe beam is weaker and the corresponding hole is less deep.

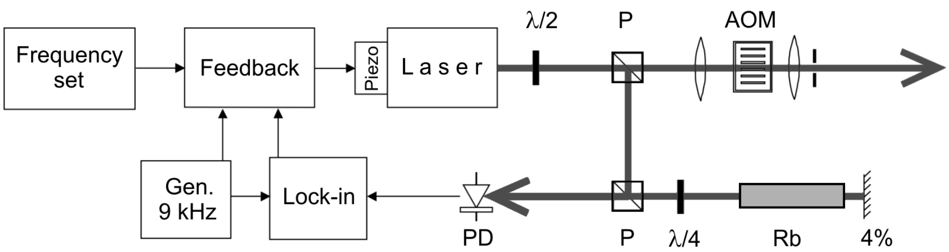

Fig. 4. Scheme of the laser stabilization using the saturated absorption method (P – the polarization beamsplitter, Rb – the atomic absorption cell, PD – the photodiode, and $\lambda/2$ and $\lambda/4$ – waveplates, AOM – the acousto-optical modulator used for shifting the laser frequency).

is not modified by the pump beam, only for exact resonance the two beams interact with the same atoms, which results in decreased absorption for the probe beam.

An example of the experimental setup for the diode laser stabilization to the Rb atomic line using the saturated absorption method is presented in Fig. 4. In this implementation the probe beam is obtained by back-reflecting the pump beam from an uncoated glass wedge. The feedback unit controls the piezo actuator, which shifts the laser resonator mirror. The modulation signal is applied to the same piezo-driven mirror. The acousto-optical modulator (AOM) at the laser output allows exact tuning of the laser frequency shift versus the atomic line.

4.3. Stabilization using atomic dichroism

Another way of stabilizing lasers to atomic transitions has been developed and used at our laboratory. It is based on measurements of the atomic circular dichroism or the difference in absorption coefficients for two circular polarizations σ^+ and σ^-. The dichroism is produced by the external magnetic field, which shifts the absorption profiles for two circular polarizations in the opposite directions. The polarimeter detector is composed of a quarter-wave plate, polarization beamsplitter, and two photodetectors. The basic experimental setup is presented in Fig. 5.

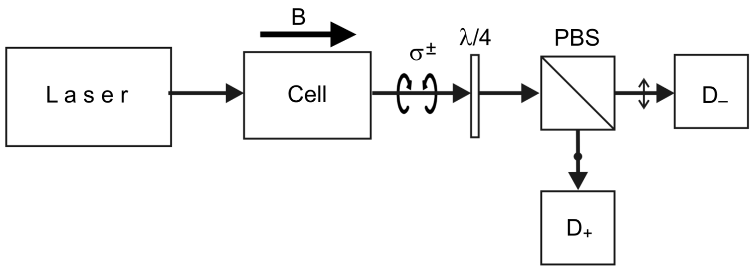

Fig. 5. Setup for the dichroism measurement (PBS – polarization beamsplitter).

The effect of dichroism has been used for the case of Doppler-broadened lines [10]–[12]. It is characterized by a strong signal, general experimental simplicity and, when used in the stabilization system, it has a broad capture range. The dichroic signal has a dispersive shape without modulation of laser frequency and can be directly used as the error signal. Figure 6 presents the Doppler-broadened dichroic signal for the D_1 rubidium line (795 nm) obtained with the 2 cm-long cell heated to 40°C placed in the

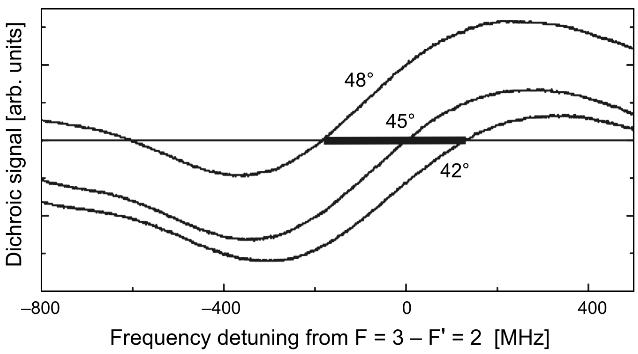

Fig. 6. Doppler-broadened dichroic signal for the D_1 rubidium line (795 nm) at 180 G magnetic field. The three recordings are taken at three positions of the quarter-wave plate angle relative to the polarization beamsplitter.

180 G longitudinal magnetic field. The signal has a distinct zero-crossing point, which serves as the locking point. The three curves in Fig. 6 correspond to three rotation angles of the quarter-wave plate relative to the polarization beamsplitter. The zero -point shift thus allows the tuning of the laser frequency within the marked range of about 300 MHz.

The laser stabilization to Doppler-broadened dichroic signal does not allow for precise locking of the laser frequency to narrower features buried within the Doppler profile. The method proposed by our group [13] overcomes these difficulties. The same idea has been independently developped by the Florence group [14]. The basic setup of the Doppler-free dichroic measurement is presented in Fig. 7.

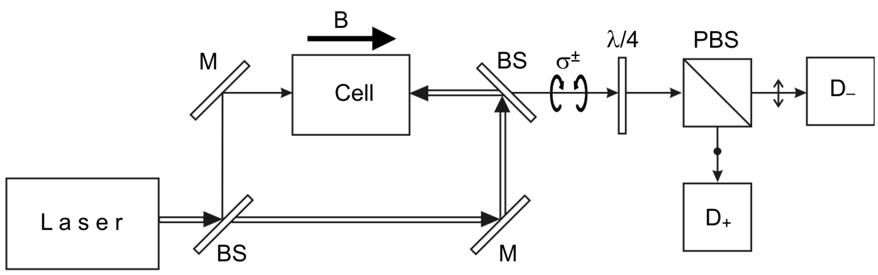

Fig. 7. Scheme of the stabilization system using the Doppler-free magnetic dichroism (the saturating laser beam is shown as a double line, the probe beam as a single line; BS – a beamsplitter, PBS – polarization beamsplitter, M – mirrors, $\lambda/4$ – quarter-wave plate, D_+ and D_- – the photodetectors measuring absorption for σ^+ and σ^- polarized light).

The atomic vapours contained in a glass cell interact with two laser beams: the strong beam causes saturation of the medium while the other, weak probe beam of linear polarization propagates in the opposite direction. It traverses the cell with atomic vapours, the quarter-wave plate, and is divided by the polarization beamsplitter. The two photodetectors measure the intensity of the transmitted light of σ^+ and σ^- polarization. The difference of the intensities recorded by two photodiodes is the measure of the dichroism induced by the weak magnetic field. Additionally, the dichroism is saturated by the strong beam. The magnetic field is supposed to produce the splitting of sub-Doppler resonances, much narrower than the Doppler-broadened curve, so the required field intensity is much lower. Figure 8**a** presents the saturated dichroism signals for the D_1 rubidium line in the Doppler-free configuration. The signals were taken with a 5 cm-long cell at room temperature at 16 G magnetic field. The dichroic signal is recorded simultaneously with the saturated absorption signal shown in Fig. 8**b**. The width of the resonances is much narrower than in the linear, Doppler-broadened case and can be used as the error signal to stabilize the laser frequency to atomic transitions.

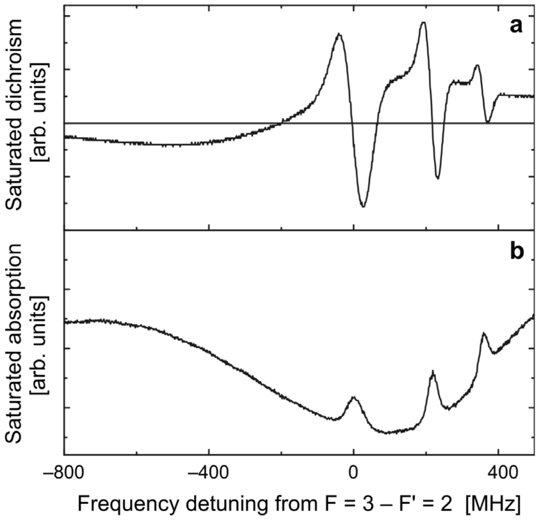

Fig. 8. Saturated dichroic signal in the Doppler-free configuration in 16 G magnetic field (**a**) and saturated absorption signal (**b**) for the D_1 rubidium line (795 nm).

The saturated dichroism signal was used to stabilize the home-built extended cavity diode laser. The obtained laser frequency stability was evaluated by recording the error signal. The amplitude of the low-frequency component was measured and multiplied by the slope of the error signal versus frequency at the lock point. This rough estimation shows that the laser stability is not worse than 0.2 MHz.

5. Application example: stability transfer

A standard method for calibration of the frequency scans in laser spectroscopy uses a transmission spectrum of laser light through a reference interferometer recorded together with the spectrum under investigation. We want to report here on a particular example of application of stabilized lasers [15], which we adopted for the experiment aiming at two-photon, step-by-step excitation of rubidium energy levels in the transition configuration 5S – 5P – 5D.

Two diode lasers with external cavities were used: one laser was locked to one of the Rb D_2 hyperfine components at 780 nm while the scan laser was tuned around the second transition at 776 nm. To reach the required precision in the two-photon spectra we needed frequency markers with no more than 40 MHz separation, which translates to the Fabry–Perot cavity (flat mirrors) about 4 m long. With the lengths that big, all instabilities caused by mechanical vibrations and air turbulence become a serious issue and make active stabilization absolutely necessary. The stabilization reference is most often a separate stabilized He-Ne laser. Since in our case one of the lasers was already stabilized to the atomic transition it served as the reference to stabilize the Fabry–Perot resonator.

The transfer cavity was a folded Fabry–Perot interferometer formed by three plane mirrors. The folding mirror was attached to a piezo actuator which controlled the cavity length, two other mirrors were used for light input and output. Total distance between the mirrors was 4 m which corresponded to free spectral range of 37.5 MHz. The input/output mirrors had low reflection coefficients of about 60% which yielded low finesse of 6 and instrumental fringe width of about 12 MHz. For high mechanical stability and elimination of air turbulences, the cavity mirrors were mounted within a 2 m-long rigid frame of an old He-Ne laser. The small, 4 nm, difference of laser wavelengths practically eliminated the possibility of spectral separation of the two beams in the cavity and, therefore, we used the polarization separation. The master and scan laser beams were orthogonally linearly polarized, combined before entering the cavity and later separated by polarization beamsplitters. Although the polarization separation was not perfect, the resulting crosstalk appeared negligible. The setup of the system is presented in Fig. 9.

Two typical recordings are presented in Fig. 10. Figure 10**a** presents the non -stabilized case and shows the transmitted intensity of the stabilized laser together with the (open loop) error signal. The cavity scan visible in the signals is caused by the thermal drift of the cavity. The recording in Fig. 10**b** was taken with active stabilization

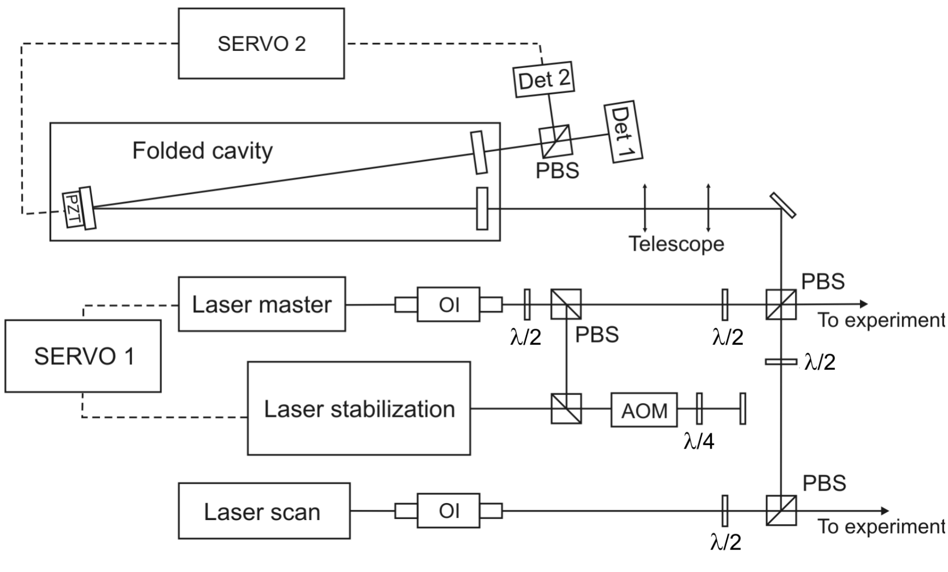

Fig. 9. Experimental setup of the two lasers and stabilized reference cavity (OI – optical isolators, PBS – polarization beamsplitters, AOM – an acousto-optical modulator used in a double-pass configuration which served to shift the locking frequency from the exact atomic resonance, as required in our experiment).

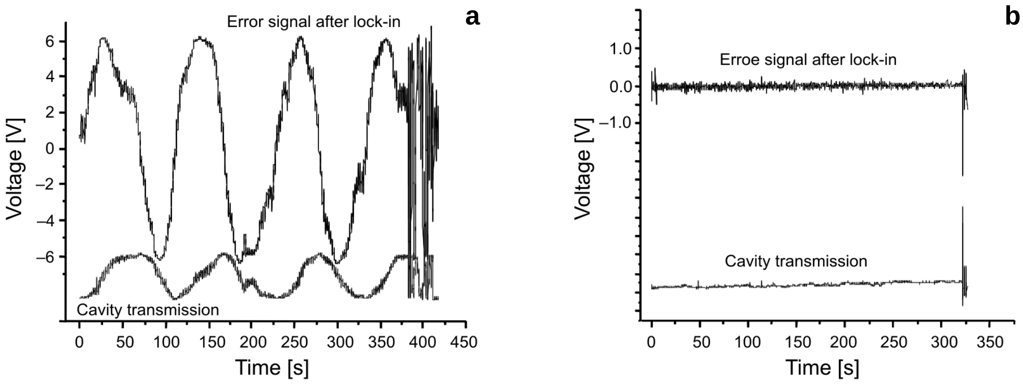

Fig. 10. Intensity of the stabilized laser measured behind the 4 m Fabry–Perot cavity and the error signal from the lock-in detector (the cavity transmission trace was displaced for clarity): non-stabilized case – thermal drift causes the cavity scan (**a**), and stabilized case – good stability of the cavity (**b**). Note the different voltage scale.

of the cavity length and proves a good stability of the reference cavity in such a case (note the vertical scale change). The thermal effects cause only a slight drift of the transmission signal caused by not perfect tuning of the feedback system. Since the correction signal is limited, after several minutes the cavity went out of lock, which is visible at the end of the recording.

We note here that the system allows the calibration of spectroscopy scans for a broad range of scan laser frequencies. The crucial feature of our system is that one of the lasers is stabilized to the atomic transition, the wavelength of the other laser is limited only by the quality of the mirror coatings as outside the wavelength band the cavity finesse decreases and the fringe quality deteriorates.

6. Conclusions

Different methods of stabilization of diode lasers have been presented. Only the simplest schemes of laser stabilization have been discussed here. More sophisticated methods which are often used are the rf-optical heterodyne lock (Pound–Drever–Hall) [16] or polarization lock (Hänsch–Couillaud) [17]. A special emphasis has been devoted to the laser stabilization to atomic references. A novel system of locking the laser frequency to the atomic transition was presented. It uses the signal of saturated atomic dichroism of atoms placed in a weak magnetic field and interacting with two counter propagating laser beams. This allows precise locking of laser frequency to sub-Doppler width resonances. The stabilization system works reliably without any modulation of laser frequency.

A system of stability transfer of the laser locked to the atomic transition onto the reference Fabry–Perot cavity has been described. The preliminary experimental system, far from being optimized, proved useful for accurate calibration of the frequency axis in the spectroscopy experiments over the measurement times of the order of a few minutes.

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