External Cavity Diode Laser Frequency Control Using FM Sideband Technique with Acousto - Optical Modulator as an External Phase Modulator

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Abstract— **A further development of a new method [1] for frequency control of the external cavity diode laser without the use of direct injection current modulation is reported. FM sideband heterodyne technique [2, 3] with AOM operating in a Raman-Nath diffraction mode as an external phase modulator and the atomic or the optical cavity resonances as the frequency references have been used to produce the error signals for high-speed servo-loop.**

I. INTRODUCTION

Reduction of the semiconductor laser frequency noise is essential in a wide range of applications in atomic physics, in metrology of a new generation of the microwave and optical frequency standards employing cooled atoms. The free running line width of the external cavity diode laser (ECDL) is of the order of a few megahertz and is limited by the mechanical and acoustical vibrations of the external cavity. Such frequency fluctuations can be suppressed by the electronical feedback to the laser diode (LD) injection current. At present, a conventional Pound-Drever FM sideband technique [2, 3] with the electro-optical modulator (EOM) as an external phase modulator is used to provide the error signals for extremely high-speed servo-loops for frequency stabilization of a variety of the lasers, including diode lasers. It has been already reported in [1] that the acousto-optical modulator (AOM) operating in a Raman-Nath diffraction mode can be used as an external phase modulator in Pound-Drever FM sideband technique converting the single mode diode laser input into a pure frequency-modulated spatially separated optical spectrum. For normal incidence of the input radiation, AOM generates frequency sidebands symmetrically spatially located around cw optical beam. Sinusoidal modulation at acoustic wave frequency Ω generates frequency sidebands at multiples of Ω around the central optical frequency ω. The amplitude of the k^{th} sideband at $\omega+k\Omega$ is proportional to $J_k(m)$, where J_k is the Bessel function of the order k and m is the peak phase modulation. The diffraction angle ϑ_k for k^{th} sideband with frequency $\omega + k\Omega$ is defined by $\sin\vartheta_k = k\lambda/\Lambda$, where λ and Λ are the light and acoustic wavelengths respectively.

Phase-sensitive detection of the sub-Doppler resonances within D_2 absorption line of Cs atom has been carried out by means of FM sideband heterodyne spectroscopy with AOM operating in a single pass Raman-Nath mode as an external phase modulator. A further development of a new method [1] for frequency control of the external cavity diode laser without the use of direct injection current modulation is reported in this paper.

II. EXPERIMENTAL SET-UP AND RESULTS

The experimental set-up is shown in Fig.1. Grating stabilized SDL-5422 (USA) and IDL150S-850 (FGUP NII "Polyus", Russia) diode lasers in a Littrow configuration with an external cavity length of 8.5 cm provided tunable single-frequency input radiation at 851nm.

The modulator was ISOMET model 1205-C2 AOM (with 80 MHz center frequency and with sweep bandwidth of 40 MHz) driven by approximately 100 mW of rf power at frequencies large compared to the 5 MHz of natural line width of the optical transitions.

The AOM output consisted only of three beams corresponding to the carrier light and to the nearest sidebands of the ±1st diffraction order with the measured diffraction angle $\vartheta_{\pm1} \cong 0.5^o$. The AOM single pass output presenting pure frequency modulated and spatially separated optical spectrum was used as a probe beam for saturated absorption spectroscopy in a magnetically shielded caesium vapour cell at room temperature and was focused on a p-i-n photo-detector PD1, which had a bandwidth of 40 MHz. The ratio of powers of each ±1st diffraction order sidebands to the carrier power in front of the input window of the Cs cell was equal to $P_{\pm1} / P_0 = 65\ \mu W / 1.75\ mW \cong 0.04$.

The rf beat was detected by the heterodyne detection using double-balanced mixer, which produced dc signal served as an error signal for our servo system. Fig.2 and Fig.3 show dispersion like shaped error signals with zero background level obtained when the laser frequency is

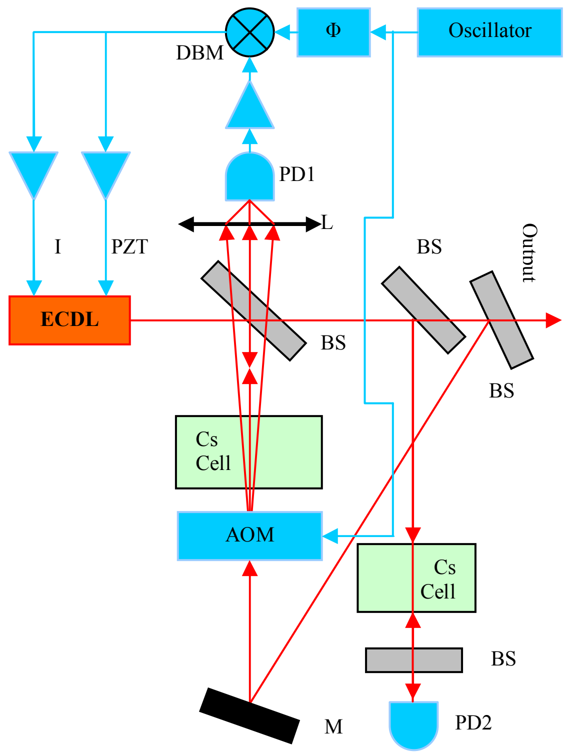

Fig.1. Experimental set-up. ECDL – external cavity diode laser; PZT – piezoelectric transducer; Φ – phase adjuster; BS – beam splitter; M – mirror; AOM – acousto-optical modulator; L – lens; PD – photo-detector; I – injection current; DBM – double-balanced mixer.

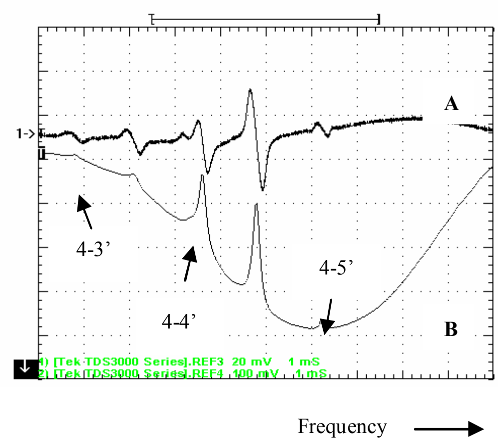

Fig.2. Curve A: error signal. Curve B: saturated absorption signal simultaneously recorded on PD2. Modulation frequency is of 30.1 MHz.

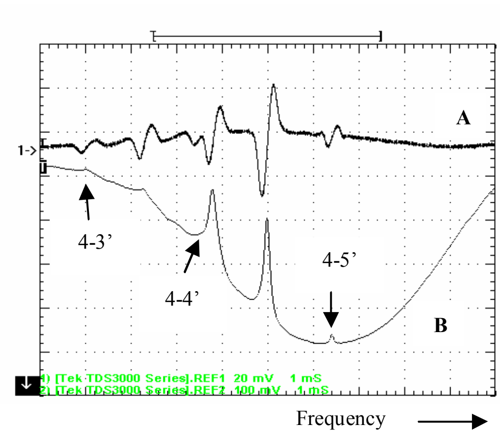

Fig.3. Curve A: error signal. Curve B: saturated absorption signal simultaneously recorded on PD2. Modulation frequency is of 34.3 MHz.

scanned across Doppler profile of caesium D_2 absorption line and coincides with the optical transition frequencies $6S_{1/2}$, F = 4 – $6P_{3/2}$, F' = 3, 4, 5, where F и F' are the total angular momenta of the atom in the ground and excited states. The only experimental parameter varied during recording of these figures. That was the modulation frequency, which had values of 30.1 and 34.3 MHz. At fixed modulation frequency, the similar change of the error signal shape and slope sign is obtained by adjustment of the phase relation between mixer input signals. This adjustment can be readily accomplished by varying the length of the cable connecting the mixer and the local oscillator.

As it was reported in [1], by varying only the local oscillator frequency we found the error signals with the appropriate shape and slope sign in a wide frequency range from about 10 MHz up to 40 MHz. Acceptable level of the obtained in a wide AOM modulation frequency range mixer output signals allowed to use them as the error signals for a high-speed servo-loop whose output correction signal was added to the laser current. A second, low-frequency servo-loop was used to compensate for slow drifts caused by thermal and mechanical perturbations.

FM sideband spectroscopy with AOM serving as an external phase modulator demonstrates the similar response to the noise sources, degrading the sensitivity of the method, as it has been described in detail in [3]. One of such detrimental effects is the presence of residual AM noise arising from the fact that the available optical phase modulators do not produce the pure FM spectrum. Small imbalance in the amplitudes of the sidebands or a relative shift in phase can prevent the beat signal from vanishing exactly. This residual AM can be detected by the photodiode and it introduces a nonzero baseline whose level can fluctuate with the laser power fluctuations. In case of using EOM as an external phase modulator, this noise can be minimized by careful control of the input and output polarizations of the light passing the EOM to balance the sidebands and by adjustment of the relative phase of the local oscillator and RF signals to minimize the offset due to the residual AM. In our case we do not care about the input and output polarizations of the light passing AOM. The balance of the sidebands is accomplished simply by the rotation of AOM in the horizontal plane and appropriate phase relation is achieved by tuning the local oscillator frequency.

To tune the laser frequency on the top of caesium saturated absorption line, we employ servo system consisting of two servo-loops: "slow" and "fast". The slow servo-loop is used to suppress low frequency noise originated from acoustic and mechanical perturbations and to compensate for slow thermal drift. The amplified and integrated output of the mixer is fed to piezoelectric transducer (PZT), which controls the grating position. The output correction signal of the fast servo-loop with wide control bandwidth (3 dB point at 6 MHz) is added to the injection current of the laser diode (LD).

The amplified beat signal from photo-detector PD1 is fed to the mixer. The mixer output signal is low-pass filtered to suppress the local oscillator frequency and its higher harmonics, and presents the error signal for our servo system and is fed to the inputs of both of servo-loops. Fig. 4 shows the electronic circuit for servo-loop controlling the laser current. By varying the modulation frequency value, the sign of the error signal can be selected. We also can change the sign of the PZT correction signal. As a result, the correct relative sign between injection current and PZT correction signals can be chosen.

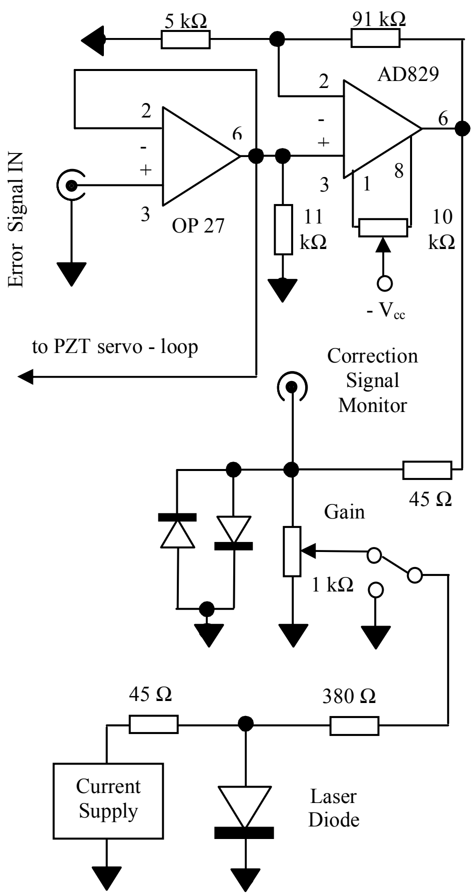

Fig. 4. Electronic circuit of the laser current servo-loop.

In order to find the optimum gain adjustment, we have carried out Fast Fourier Transform (FFT) analysis of the current and PZT correction signals. When the laser frequency was tuned to the top of the saturated absorption signal with PZT control loop closed and laser current control loop open, we intentionally increased the PZT loop gain until PZT started to oscillate at frequency about 1.5 kHz, and the noise sidebands appeared on the spectra of both of the analyzed correction signals due to the unstable operation of the PZT control loop (black curves in Fig. 5, 6).

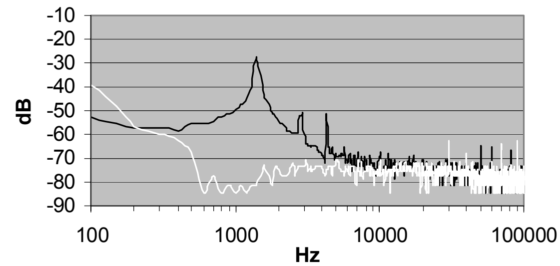

Fig. 5. Spectrum of the PZT correction signal. Black curve: injection current servo-loop is open. White curve: injection current servo-loop is closed AOM modulation frequency is of 40 MHz.

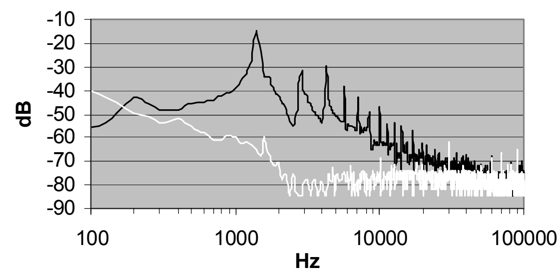

Fig. 6. Spectrum of the injection current correction signal. Black curve: injection current servo-loop is open. White curve: injection current servo-loop is closed AOM modulation frequency is of 40 MHz.

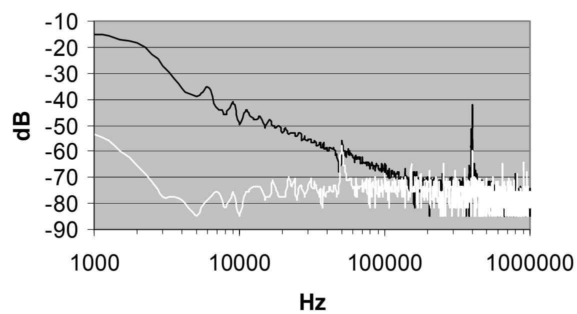

Fig. 7. Spectrum of the injection current correction signal. Black curve: injection current servo-loop is open. White curve: injection current servo-loop is closed AOM modulation frequency is of 39.6 MHz.

When we closed the current loop and increased gradually its gain starting with zero gain point, wideband frequency noise suppression on the spectrum of each correction signal was observed (white curves in Fig. 5, 6). Thus, the monitoring of the correction signals provides useful information on the magnitude and on the spectral distribution of the frequency noise to be compensated, as well as on the loop control bandwidth. For instance, at AOM modulation frequency of 39.6 MHz besides the noise due to the PZT oscillation (black curve in Fig. 7), one can see the noise spike on the spectrum of the current correction signal at frequency about 400 kHz which have been suppressed after the injection current loop has been closed (white curve in Fig. 7).

At present, we posses only one laser system described in this paper, and for that reason we are not able to estimate the locked laser emission spectrum width with certainty. We have carried out the spectrum analysis of the beat signal between our laser and commercial laser system DL 100 "TOPTICA" (Germany). The laser system DL 100 presents the grating stabilized external cavity diode laser with servo system employing the laser injection current modulation. The width of the beat signal was about 2 MHz at 3 dB level. The repeat of the procedure described above, i.e. an intentional excitation of the slow loop (that have resulted in appearance of the noise sidebands on the beat signal spectrum in ±5 MHz bandwidth around 2 MHz central beat signal) and subsequent suppression of the induced sidebands after the injection current loop has been closed, has shown that the control bandwidth of our laser servo system can be estimated on a MHz scale.

The spatial separation and divergency of the frequency sidebands generated by AOM in a Raman-Nath mode around the central optical beam is not, in our opinion, a severe obstacle to use the resonances of the confocal Fabry-Perot cavity as the frequency references for the Pound-Drever spectroscopy. Fig. 8 shows the experimental set-up we used to get the mixer reference input signals for that case. For appropriate focal lengths of the L1 and L2 lenses forming telescope system with AOM in between, the cavity input represents three collimated and parallel beams corresponding to the carrier light and to the nearest sidebands of the ±1st diffraction order. Again, by varying the AOM modulation frequency we observed the error signal slope sign reversal at different frequencies in 10 MHz - 40 MHz range.

III. Conclusions

Presented simple and efficient method of the FM heterodyne spectroscopy with AOM operating in a Raman-Nath diffraction mode as an external phase modulator can be used to obtain the error signals in a wide modulation frequency range for the high-speed servo-loops for frequency tuning of the external cavity diode lasers to the atomic or to the optical cavity resonances.

In locked diode laser conditions, spectrum analysis of the laser emission has shown wide-bandwidth, on a MHz scale, frequency noise suppression.

The experimental set-up is proposed to employ the resonances of the high finesse confocal Fabry-Perot cavity as the frequency references for Pound-Drever FM sideband spectroscopy with AOM serving as an external phase modulator.

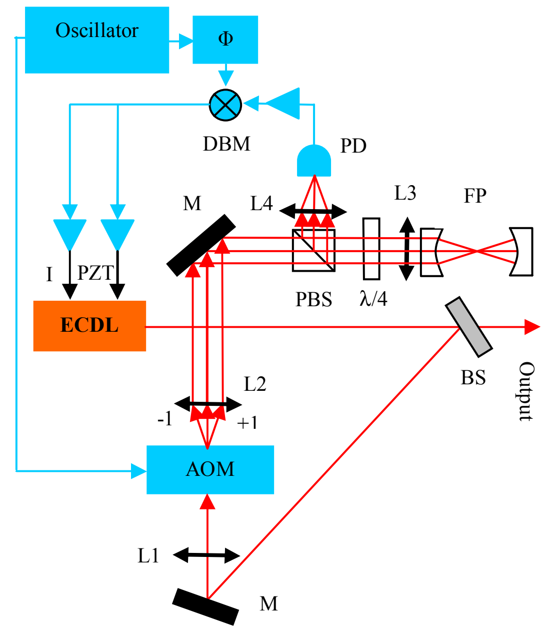

Fig.8. Proposed experimental set-up for FM sideband spectroscopy with Fabry-Perot cavity resonances as the frequency references. ECDL – external cavity diode laser; PZT – piezoelectric transducer; Φ – phase adjuster; BS – beam splitter; M – mirror; AOM – acousto-optical modulator; L – lens; PD – photo-detector; I – injection current; DBM – double-balanced mixer; FP – Fabry-Perot confocal cavity; PBS – polarizing beam splitter; λ/4 – quarter wave plate.

References

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