Reproducibility of the frequency of an He-Ne laser with a methane absorbing cell

S. N. Bagaev, E. V. Baklanov, E. A. Titov, and V. P. Chebotaev

Semiconductor Physics Institute, Siberian Division, USSR Academy of Sciences

(Submitted July 5, 1974)
ZhETF Pis. Red. 20, No. 5, 292–296 (September 5, 1974)

1. Nonlinear optical resonances serve as reference points for the stabilization of laser frequencies. By tuning the frequency to resonance it is possible to obtain high reproducibility of the frequency, i. e., high accuracy with which the laser-emission frequency can be reproduced from switching to switching. This characteristic of the lasers is of greatest interest for scientific and practical applications of frequency-stable lasers. Different physical factors affect the positions and shapes of the resonances, and consequently the frequency reproducibility.

The collision shift,[1] the quadratic Doppler effect,[2] and the recoil effect[3] offer no obstacle to the attainment of a frequency reproducibility 10^{-13}–10^{-14}, which was obtained with the aid of an He-Ne laser with a methane cell.[1,2] A magnetic hyperfine structure (mhfs) was recently observed theoretically[4] and experimentally[5] on the methane transition with $\lambda = 3.39\ \mu$ [$F_2^{(2)}$ component of the $P(7)$ line of the ν_3 band], and was used for frequency stabilization. The nonlinear power resonance is produced mainly by three strong mhfs components, the transition frequencies ω_k of which can be expressed in the form $\omega_k = \omega_0 + k\Delta$ ($k = 0, \pm 1$), where $\Delta = 14.2$ kHz[4] and 11.4 kHz.[5] The intensities of the considered three components have a ratio 0.85 : 1 : 1.15.[4] Different saturations of the mhfs components lead to an additional influence of the field and of the pressure on the position of the resonance, and this can limit the laser-frequency reproducibility to the $\sim 10^{-12}$ level.[4,5]

In this paper we describe experiments on frequency reproducibility and present the results of theoretical investigations of the influence of the mhfs on the position of the resonance. Analysis has shown that in certain operating regimes of an He-Ne laser with absorbing cell, the mhfs does not prevent attainment of a reproducibility 10^{-13}–10^{-14}, in agreement with the results of[1,2].

2. The experiments were performed with two He-Ne lasers. The beam diameter in the absorption cell was

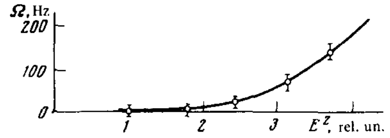

FIG. 1. Experimental variation of the frequency shift of a laser stabilized against the power peak with changing field in the resonator.

~1 cm, the cell length was ~3 m, and the active part was ~2 m long. The detailed procedure of the measurements of the laser-frequency difference with the aid of an acoustic modulator, and the results of the investigations of the frequency stability, are given in[6]. The use of a laser with a long absorption cell and with a large beam diameter in the amplifying and absorbing tubes has made it possible to obtain intense resonances of width 30—50 kHz at low gas pressures, $5\times10^{-4}-10^{-3}$ Torr, and at low absorption saturations (saturation parameter $\kappa = 0.1-0.3$). The tuning to the peak of the resonance was monitored by the vanishing of the error signal in the automatic frequency control (AFC) system, with the laser-emission frequency modulated at a modulation frequency 15 kHz. The resonance parameters were such that the amplitude of the laser-frequency deviation could be reduced to several hundred Hz, and the influence of the parasitic Q modulation, which affected the frequency reproducibility, was greatly decreased. Figure 1 shows the frequency shift of one of the lasers as a function of the field in the resonator. In weak fields (saturation parameter 0.1—0.3), a twofold change of the field produced a frequency shift of ± 20 Hz. The sign and magnitude of the shift were determined mainly by the tuning of the laser resonators and of the AFC systems. Near the optimal regime for stabilization, the rms deviation obtained in 30 independent laser tunings was 4.5 Hz (3.2 Hz for one laser). The average values of the difference frequency differed by not more than 2 Hz. The generation power was chosen to be optimal for the production of the error signal, so that identical saturation parameters ($\kappa \sim 0.3$) could be established in the cells of both lasers.

In contrast to other studies, in our experiments the modulation frequency was close to the half-width of the resonance, and the modulation index was much smaller than unity. The emission spectrum contained in this case two sideband frequencies. A stabilized laser-emission frequency corresponds to a position whereby the absorption of the weak component of the FM signal is the same, and there is no amplitude modulation of the output signal. The contour asymmetry due to the mhfs causes this frequency to be different from the maximum of the resonance (Figs. 2 and 3).

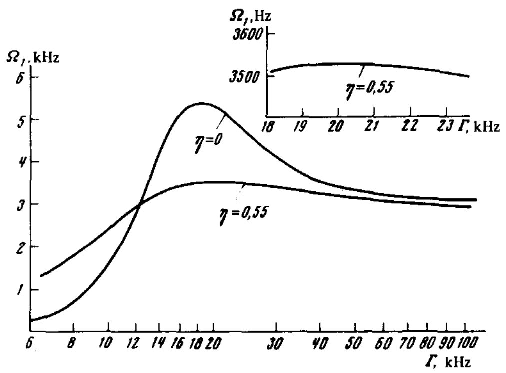

FIG. 2. Shift of stabilized laser frequency, due to mhfs of methane, with changing pressure (Γ is the half-width of the individual mhfs component and depends on the pressure).

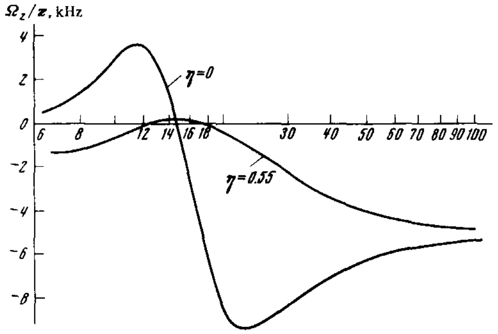

FIG. 3. Field dependence of the shift of the stabilized laser frequency.

We have solved the problem of the absorption of a frequency-modulated signal in the field of a standing wave with allowance for three strong mhfs components, accurate to fourth order in the field. The detuning Ω of the stabilized frequency relative to the central mhfs component is given by

$$\Omega = \phi(\Gamma, \Delta, \eta) + \kappa F(\Gamma, \Delta, \eta), \tag{1}$$

where Γ is the half-width of the individual component and is determined by the collisions, $\eta = f/2\Delta$, f is the modulation frequency, $\kappa = 2|d_0|^2E^2(\gamma_m^{-1}+\gamma_n^{-1})/\hbar^2\Gamma$ is the parameter of the saturation on the $k = 0$ transition, d_0 is the dipole matrix element of the transition, γ_m and γ_n are the reciprocal lifetimes of the upper and lower levels, and $2E$ is the amplitude of the standing-wave field.

The results of calculation of the functions $\Omega_1 = \phi(\Gamma, \Delta, \eta)$ and $\Omega_2 = \kappa F(\Gamma, \Delta, \eta)$ for $\eta = 0$ (maximum of the resonance and $\eta = 0.55$ are shown in Figs. 2 and 3. An analysis of the curves shows that in the presence of mhfs the use of frequency modulation greatly decreases the dependence of the frequency shift of the stabilized laser on both the pressure (i.e., on Γ) and the field.

4. Inasmuch as the saturation parameter can be chosen to be very small, principal importance attaches to the dependence of Ω on the pressure, described by the first term in (1). As follows from Fig. 2, at $\Gamma \sim 20$ kHz (pressure $\sim 10^{-3}$ Torr), when the pressure is changed by 10% at $\eta = 0.55$ ($\Delta \sim 14$ kHz), the value of Ω_1 ranges from 3 to 10 Hz, thus explaining the reproducibility obtained in[1,2] for the frequency as a function of the pressure. Let us estimate the influence of the field on the frequency shift. Figure 3 shows that not only the magnitude but also the sign of the field shift depends on Γ. In the region $\Gamma \sim 11-20$ kHz at $\kappa \sim 0.3$, when changes by 10%, the field-induced frequency shift ranges from 4 to 10 Hz and agrees with experiment.

Thus the frequency stabilization used in[1,2] ensures a reproducibility $10^{-13}-10^{-14}$. We note that the frequency-stabilization regimes used in other studies[7-9] are not optimal for the attainment of this reproducibility. At $\Gamma \sim 100$ kHz and $\kappa \sim 1$, a 10% change of the field leads to shifts ~300 Hz, thus limiting the reproducibility to the $10^{-11}-10^{-12}$ level, in accord with the results of[7-9].

We note in conclusion that the described method of tuning to resonance can greatly decrease the influence of other physical factors (the quadratic Doppler effect, the recoil effect, etc.) on the frequency reproducibility.

The authors are deeply grateful to L. S. Vasilenko and B. I. Troshin for useful advice and discussions, to K. A. Bikmukhametov for great help with the control experiments, and to Yu. P. Tkachenko and A. K. Maslov for help with the construction of the setup.

[1] S. N. Bagaev, E. V. Baklanov, and V. P. Chebotaev, ZhETF Pis. Red. **16**, 344 (1974) [JETP Lett. **16**, 243 (1972)].
[2] S. N. Bagaev and V. P. Chebotaev, ZhETF Pis. Red. **16**, 614 (1972) [JETP Lett. **16**, 433 (1972)].
[3] E. V. Baklanov, Nelineĭnye protsessy v optike (Nonlinear Processes in Optics), No. 3, 117 (Proceedings of Third Vavilov Conference on Nonlinear Optics, 1973).
[4] K. Shimoda, Japan. J. Appl. Phys. **12**, 1393 (1973).
[5] J. L. Hall and C. Borde, Phys. Rev. Lett. **30**, 1101 (1973).
[6] S. N. Bagaev and V. P. Chebotaev, Nelineĭnye protsessy v optike (Nonlinear Processes in Optics), No. 3, 107 (Proceedings of Third Vavilov Conference on Nonlinear Optics, 1973).
[7] R. L. Barger and J. L. Hall, Phys. Rev. Lett. **22**, 4 (1969).
[8] N. V. Koshelyavskiĭ, V. I. Tatarenkov, and A. N. Titov, ZhETF Pis. Red. **15**, 461 (1972) [JETP Lett. **15**, 326 (1972)].
[9] N. G. Basov, M. V. Danileĭko, and V. V. Nikitin, ZhETF Pis. Red. **12**, 95 (1970) [JETP Lett. **12**, 66 (1970)].