H_c, and that the current density in the remainder of the sample is constant, it is easy to express I_L in terms of I_0, I_b, and I_c. The satisfactory agreement between the points obtained in this manner and the experimental curve on Fig. 1 confirms the foregoing assumptions.

Whenever I_0 and I_b had the same sign, the coil placed on the inner surface made it possible to reveal the vanishing of the t.m. layer when I_b reached the value $(d_1/d_2)I_c$ at which the field on the outer surface was equal to the critical value.

Thus, layers of the t.m. state can exist in doubly-connected samples of type-II superconductors. If we neglect their thickness, these layers are magnetic-field discontinuity surfaces. The magnetic-field discontinuity is $\Delta H = 2H_c$ if the layer is inside the sample and $\Delta H \leq 2H_c$ when the layer is on the sample surface.

The diagram of the states of a hollow cylindrical sample at different values of I_b and of the sum $I_0 + I_b$ should have, in accord with the foregoing representations, the form shown in Fig. 2 (for currents I_0 small compared with the current needed to destroy the t.m. layer, which is our case exceeded I_c by several tens of times).

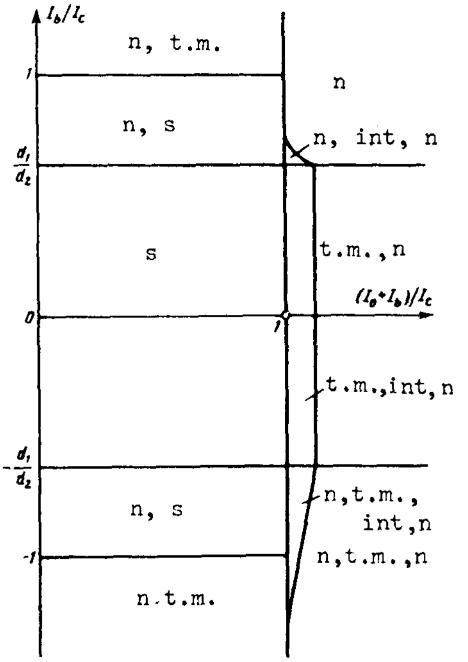

Fig. 2. Diagram of states of hollow cylindrical sample. For each region, the states of the coaxial layers in the sample are listed from the inside layer to the outside one; s - superconducting state, n - normal, i - intermediate, t.m. - two-dimensional mixed state.

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[1] I.L. Landau and Yu.V. Sharvin, ZhETF Pis. Red. 10, 192 (1969) [JETP Lett. 10, 121 (1969)].
[2] B.P. Peregud, Prib. Tekh. Eksp. No. 3, 64 (1957).

TWO-FREQUENCY OPTICAL STANDARD

S.N. Bagaev, A.K. Dmitriev, and V.P. Chebotaev
Institute of Semiconductor Physics, Siberian Division, USSR Academy of Sciences
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1. We report here for the first time observation of narrow resonances in the radiation power of a gas laser with nonlinear absorption in a stable regime of generation of two longitudinal modes that are symmetric about the center of the absorption line, and stabilization of the frequency in this generation regime with a small value of frequency instability ($\Delta\nu/\nu = 10^{-12}$). The obtained highly-stable generation of two oscillation modes permits a) an appreciable extension of the capabilities of optical frequency standards,

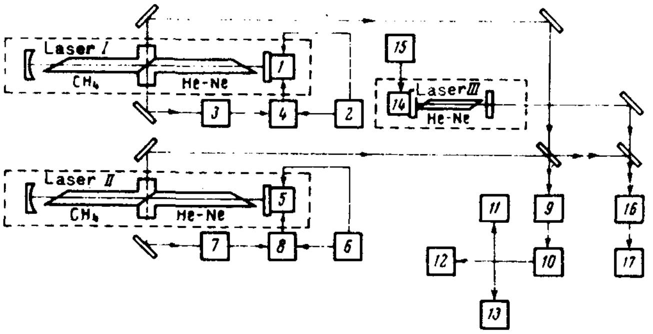

Fig. 1. Block diagram of experimental setup: 1, 5, 14 - piezoceramic element, 2, 6, 15 - acoustic generator, 3, 7, 9, 16 - photoreceiver, 4, 8 - automatic frequency control, 10 - broadband amplifier, 11 - frequency meter, 12 - spectrum analyzer, 13, 17 - oscilloscope.

b) development of fundamentally new interferometer systems for exact measurements of large distances, and c) construction of secondary standards for the microwave band based on highly stable photodetector oscillations obtained by mixing optical signals of different frequencies. It is undoubtedly of interest to use the obtained regime of generation of two symmetrically placed modes for the investigation of quantum fluctuations and of the dependence of the Lorentz width on the translational velocities of the colliding particles.

The formation of narrow resonances in the two-frequency regime can be explained on the basis of Lamb's theory [1], and also by using the model wherein Bennet "dips" are produced in the atom velocity distribution under the influence of opposing waves [2]. It is easy to show (see, e.g., [3]) that opposing waves with different frequencies will interact with the same atoms only if the frequencies are symmetric about the relative center of the gain (absorption) line. Nonlinear interaction of these two waves with a gas, just as in the case of a standing wave [1], leads to formation of a dip in the gain (absorption) line and consequently to the appearance of narrow resonances in the generation power when the length of the Fabry-Perot resonator is varied (which changes the placement of the modes relative to the line center). This phenomenon was not observed so far in lasers without nonlinear absorption with Fabry-Perot resonators, because the regime of generation of two symmetrical longitudinal modes is unstable, owing to their competition [4, 5]. A different situation can take place in a laser with nonlinear absorption, where a stable regime of generation of two and more longitudinal modes near their symmetric arrangement relative to the center of the absorption line is possible [6]. In this case one can expect a decrease of the absorption for the opposing waves, which leads naturally to the formation of a generation power peak when the length of the resonator is varied.

3. Observation of narrow resonances of the two-frequency regime and the frequency stabilization were realized in a setup (Fig. 1) consisting of two identical He-Ne lasers I and II operating at $\lambda = 3.39$ μ with internal methane absorption cells[1]. Laser III was a heterodyne used to determine the frequency composition and the arrangement of the modes of the investigated lasers I and II. In the absence of absorbing gas in the cell, eash laser usually generated at three modes. Introduction of the methane resulted in a single-frequency regime. The selecting ability of a methane cell in an He-Ne laser was noted earlier in [12]. Further increase of the methane absorption leads to a jumpwise change to generation of two frequencies symmetric about the center of the

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[1] The use of methane as a nonlinear absorber in gas lasers was proposed for auto-stabilization of the frequency at the center of the absorption line in [7] and to obtain a narrow power peak in [8]. The power peak of the He-Ne laser radiation at $\lambda = 3.39$ μ with a methane cell and its use for frequency stabilization were first realized in [9]. Very contrasty resonances were observed in methane through competition of opposing waves in a laser with a ring resonator [10] and recently in a laser with a Fabry-Perot resonator with interaction of waves with orthogonal polarizations [11].

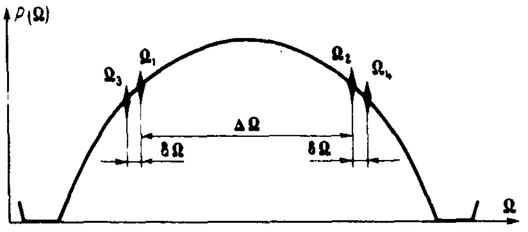

Fig. 2

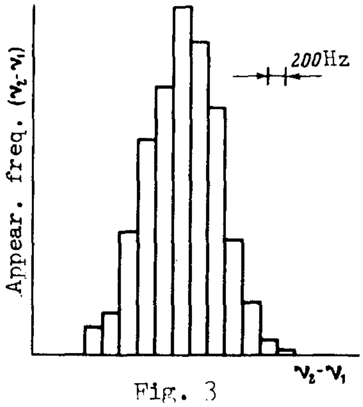

Fig. 3

Fig. 2. Output power of laser III vs. frequency. The beat signals correspond to frequencies Ω_1 and Ω_2 of laser I and Ω_3 and Ω_4 of laser II.

Fig. 3. Histogram of distribution of readings of the laser difference frequency near $\delta\Omega = 2.8$ MHz. Measurement time $t = 20$ min. Averaging time $\tau = 1$ sec.

absorption line. We attribute this to the change in the line shape of the resultant amplification in the two-component medium (in our case, the centers of the gain and absorption lines coincided). The frequency difference between the generated modes was usually 450 MHz. The region of continuous variation of the frequency was ∿100 MHz. When the resonator length was varied, a peak appeared in the generation power and had a contrast of about 3% and a width on the order of 300 kHz. By adjusting the resonator length to produce a maximum power peak it was possible to stabilize the positions of the generated modes relative to the line center, and consequently to stabilize the emission frequency of each mode, as well as their difference. The arithmetic mean of the generation frequency is equal in this case to the frequency of the center of the absorption line.

4. The position and absolute frequency of each of the two generated modes is determined by the distance between the mirrors and by the difference of their longitudinal indices. In the case of symmetrical arrangement of the modes, in each laser, the frequency deviation between the pair of closely-lying modes of lasers I and II is equal to (see Fig. 2)

$$\delta\Omega = (\Omega_1 - \Omega_3) = \frac{1}{2}\left(\frac{c}{2L_1}\Delta n_1 - \frac{c}{2L_2}\Delta n_2\right),$$

where c is the speed of light, L_1 and L_2 are the optical lengths, and Δn_1 and Δn_2 are the differences of the longitudinal indices of the generated modes of lasers I and II, respectively. In our experiments $\delta\Omega$ was equal to 2.8 MHz. By measuring the optical characteristics of the beat signal produced by mixing the radiation from the two lasers at this frequency one can assess the stability of the gas laser emission at each generated mode. Since Ω_1 and Ω_2 of both lasers differ by a sufficient amount, capture and pulling effects in such a system can be neglected. It was found that the short-time instability of the frequencies of one laser amounts to 4×10^{-11} (averaging time $\tau = 10^{-3}$ sec, smaller by approximately one order than the characteristic perturbation time). The frequency instability at an averaging time 1 sec turned out to be 3×10^{-12}. A histogram of the distribution of the frequency readings near 2.8 MHz at $\tau = 1$ sec is shown in Fig. 3. It seems that at the attained frequency stability of each mode, the stability of the difference frequency $\Delta\Omega$ is determined by the quantum fluctuations.

[1] W.E. Lamb, J. Phys. Rev. 134A, 1429 (1964).
[2] W.R. Bennett, J. Phys. Rev. 126, 580 (1962).
[3] E.V. Baklanov and V.P. Chebotaev, Zh. Eksp. Teor. Fiz. 60, 552 (1971) [Sov. Phys.-JETP 33, 300 (1971)].
[4] S.A. Gonchukov, I.O. Leipunskii, E.D. Protsenko, and A.Yu. Rumyantsev, Opt. spektr. 27, 313 (1969).
[5] R.L. Fork and M.A. Pollack, Phys. Rev. 139, A1408 (1968).
[6] I.M. Beterov, V.I. Lisitsyn, and V.P. Chebotaev, Opt. spektr. 30, 932 and 1108 (1971).
[7] V.S. Letokhov, ZhETF Pis. Red. 6, 597 (1967) [JETP Lett. 6, 101 (1967)].
[8] V.N. Lisitsyn and V.P. Chebotaev, Zh. Eksp. Teor. Fiz. 54, 419 (1968) [Sov. Phys.-JETP 27, 227 (1968)].
[9] N.G. Basov, E.M. Belenov, M.V. Danileiko, and V.V. Nikitin, ibid. 57, 1991 (1969) [30, 1079 (1970)].
[10] R.L. Barger and J.L. Hall, Phys. Rev. Lett. 22, 4 (1969).
[11] M.A. Gubin, A.I. Popov, and E.D. Proshchenko, Collection: Kvantovaya elektronika (Quantum Electronics), Sov. Radio, No. 3, 99 (1971).
[12] N.G. Basov, M.V. Danileiko, and V.V. Nikitin, Zh. Prikl. Spektr. 11, 3 (1969).

ERRATA

In the article by S. N. Bagaev et al., Vol. 15, No. 2, p. 64, references [9] and [10] should be interchanged.