GENERAL

Ultraweak optical pumping of a rubidium frequency discriminator

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(Submitted December 25, 1987)
Zh. Tekh. Fiz. **58**, 1116–1121 (June 1988)

Experimental data reported in the paper support previous recommendations by the authors for a radical reassessment of the optical pumping conditions for rubidium frequency standards. The recommendations were that the pump intensity be reduced to one-tenth the customary value and were aimed at sharply increasing the long-term stability of the frequency standard without reducing the short-term stability.

1. In previous papers,[1,2] we made a theoretical study of the influence of the optical pump intensity I on the quality factor Φ (I) of the reference 0–0 resonance in Rb vapor. The quality factor, which is equal to the ratio of the amplitude of the magnetic resonance signal to the width of the resonance[1]) and to the rms noise level, determines the allowable accuracy in fixing the resonance peak and characterizes the short-term stability of the frequency of an oscillator tuned to resonance with the reference transition. In Refs. 1 and 2 we showed that the quality factor Φ (I), optimized with respect to the value of the resonance-inducing microwave field H, is a single-valued function of the pump intensity. This function has one maximum, whose magnitude and position depend on the pump efficiency $Q = (W_1 - W_2)/(W_1 + W_2)$, where W_1 and W_2 are the rates of excitation (averaged over the volume of the unit cell) of Rb atoms by optical pumping from the F = 1 and F = 2 sublevels of the ground state.

The expression for Φ (I) in Refs. 1 and 2 was obtained on the assumption that shot fluctuations of the photodetector current are the only source of noise in the signal channel. In the case of the maximum pump efficiency (Q = 1) the maximum of Φ (I) is reached at the relative intensity $I_0 = (W_1 + W_2)/2\gamma_0 = (\gamma - \gamma_0)/\gamma_0 = 1.16$, which corresponds to a resonance width γ increased to 2.16 times the dark width γ_0 as a result of excitation.

As was mentioned in Refs. 1 and 2, this optimal value of the intensity is roughly an order of magnitude smaller than that in actual rubidium standards. The recommended sharp reduction of the pump light promises not only to increase the short-term frequency stability of the standard but also to decrease the slow frequency drifts linearly with the lowering of the pump intensity, since these drifts are determined primarily, directly or indirectly, by optical perturbations of the frequency of the 0–0 transition.

2. The experiment shows (see below) that the maximum quality factor, which is limited by the photocurrent shot noise, reaches 10^3 $Hz^{-1}s^{1/2}$ at the optimal light intensity I_0. Such a high value of Φ (I_0), however, is not attained because of the amplitude–phase fluctuations of the microwave field that induces the 0–0 resonance. It is easily seen that the phase fluctuations occurring in the vicinity of the doubled resonance scanning frequency Ω produces in the signal channel a noise N_Φ proportional to the slope of the resonance, g(I) = Φ(I)·N_{sh}, where N_{sh} is the photocurrent shot noise, i.e.,

$$N_\varphi = k_1\Phi(I)N, \tag{1}$$

where k_1 is the proportionality factor of the average random deviation of the frequency of the microwave field.

The amplitude fluctuations of the microwave field with a frequency in the vicinity of Ω generate a noise N_a in the signal channel that is proportional to the amplitude of the resonance signal S (I) = g(I)·Γ(I), where $\Gamma(I) = \sqrt{3}(1 + I)\gamma_0$ is the width of the resonance with allowance for the light-and field-induced broadening. Thus

$$N_a = k_2\Phi(I)N_{sh}\Gamma(I), \tag{2}$$

where k_1 is a coefficient that is proportional to the relative amplitude fluctuations.

In the absence of a correlation between the phase and amplitude fluctuations the total noise is $N = \sqrt{N^2_{sh} + N^2_\Phi + N^2_a}$, and the quality factor F(I) with allowance for the noise of the microwave field is

$$F(I) = \Phi(I)\left[1 + \left(\frac{N_\varphi}{N_{sh}}\right)^2 + \left(\frac{N_a}{N_{sh}}\right)^2\right]^{-1/2}. \tag{3}$$

Using the expressions for N_Φ and N_a, we can easily obtain the explicit form of the dependence of the real quality factor F(I) on the pumping intensity in terms of the previously known function Φ(I),

$$F(I) = \Phi(I)[1 + \Phi^2(I)(k_1^2 + k_2^2 \cdot 3(1 + I)^2\gamma_0^2)]^{-1/2}. \tag{4}$$

To make comparison with experiment more convenient we express F(I) in terms of the easily measured ratios of the noises in the signal channel

$$F(I) = \Phi(I)\left[1 + \frac{\Phi^2(I)}{\Phi^2(I_0)}\left(\theta_1^2 + \theta_2^2\frac{(1 + I)^2}{(1 + I_0)^2}\right)\right]^{-1/2}, \tag{5}$$

where

$$\theta_1 = \frac{N_\varphi(I_0)}{N_{sh}(I_0)} = k_1\Phi(I_0), \quad \theta_2 = \frac{N_a(I_0)}{N_{sh}(I_0)} = k_2\Phi(I_0)\Gamma(I_0).$$

Figure 1 shows a family of calculated F(I) curves for various fluctuations of the microwave field. The solid lines are for the case when only phase fluctuations exist, and the dashed lines are for purely amplitude fluctuations. The upper curve corresponds to the absence of fluctuations of the microwave field, i.e., coincides with Φ(I). Figure 1 suggests that the noise of the microwave field reduces the quality factor and, moreover, substantially changes its dependence on the pump intensity, making it desirable

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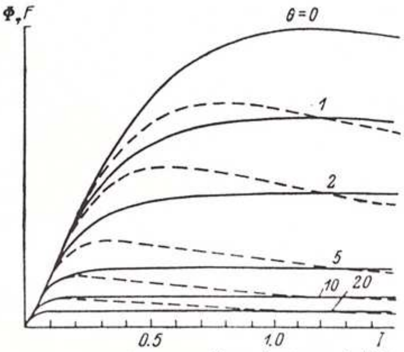

FIG. 1. Maximum quality factor Φ (I) and real quality factor F(I) of the 0–0 resonance as functions of the optical pumping intensity I.

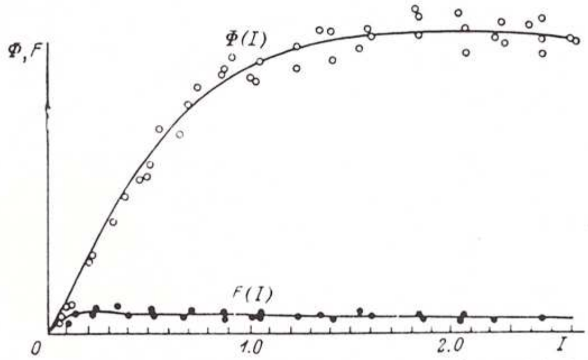

FIG. 2. Theoretical (solid lines) and experimental (points) curves Φ (I) and F(I); Q = 0.66, $\theta_1 = \theta_2 = 11$.

to reduce the intensity further relative to the value I_0, which is optimal in the absence of such noise.

The specific recommendations depend on the quality of the oscillator and the frequency synthesis and multiplication system used.

3. The foregoing assumptions were checked in detail experimentally. The setup was assembled on the standard scheme.[3] Resonance was excited in rubidium vapor in a 55 × 55-mm cylindrical cell in a mixture with argon and nitrogen with a partial-pressure ratio of 0.55:1 and a total pressure of 5 torr. The dark width γ_0 of the resonance was 29 Hz at a temperature of 44°C. Pump light from ^{87}Rb lamp was filtered with a cell containing ^{85}Rb vapor mixed with nitrogen at a pressure of 125 torr. The filter temperature of 60°C corresponded to a pump efficiency Q ≈ 0.6.

The shape of the resonance line was recorded by means of slow frequency pulling of the microwave field with a simultaneous 100% amplitude modulation of the field. The relative pump intensity I was determined from the value of the optical broadening of the resonance. The microwave field intensity was optimized for each value of the pump intensity.

Figure 2 shows the experimental plots of Φ(I) and F(I). To determine Φ(I) we measured the amplitude and width of the resonance and the noise of the signal channel with the microwave field switched off. The noise was predominatly photocurrent shot noise. The F(I) measurements were carried out in similar fashion, but the noise was measured with the microwave field switched on. The results of the measurements are indicated by the points in Fig. 2. The scatter of the points is due to the random scatter of the noise measurements. The solid lines represent the calculated Φ(I) and F(I) curves. The maximum values of the functions served as the fitting parameters. The ratio θ_1/θ_2 was obtained by measuring the noise with the frequency pulling of the microwave field switched off.

When the microwaves are tuned to the peak of the resonance, only the amplitude fluctuations of the field appear. The phase fluctuations make the maximum contribution to the noise when the microwaves are tuned to the slope of the resonance at maximum steepness. From these measurements we found that $\theta_1/\theta_2 \approx 1$.

Examination of Fig. 2 graphically demonstrates the desirability of lowering the pump intensity to a value of 0.1-0.2, which is 1/100 to 1/50 of the intensities used in practice.

As a supplementary illustration we give more detailed results of several measurements of the quality factor of the 0–0 resonance with the experimental setup under slightly different conditions. The operating temperature of the cell was lowered to 30°C, causing the dark width of the resonance to decrease to ~21 Hz. Pumping was effected with the light of one D_2 line (7800 Å). The temperature of the isotopic filter was raised to 70°C and as a result the pump efficiency Q increased to 0.97. The shape of the resonance shown in Fig. 3a was recorded when the power of the microwave field was low (1) and optimal (2). The pump intensity was set at the level I = 0.1, which corresponded to a photocurrent I_{ph} = 0.8 μA of the FD-7K photodiode that detected the light transmitted through the cell. Figure 3 shows fragments of the record of the noise of the signal channel with the microwave field switched on, without the field, and with the photodiode covered. These records were taken with a calibrated 100-fold increase in the signal-channel gain. Processing of these records gives $F = 130\ \mathrm{Hz}^{-1}\ \mathrm{s}^{1/2}$, which serves as a good illustration of the serviceability of the system under conditions of "ultraweak" light intensity.

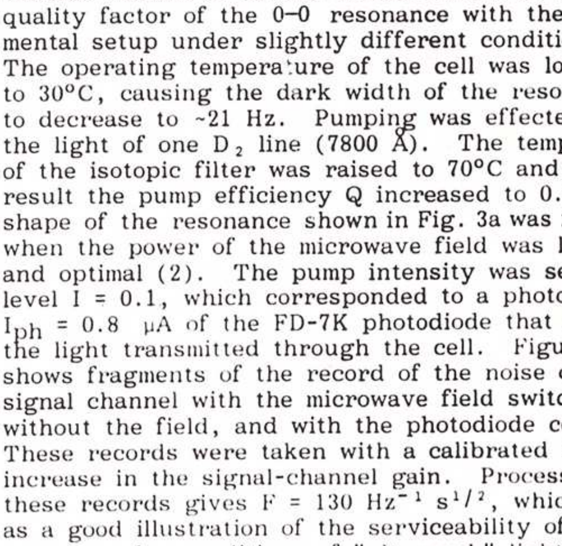

FIG. 3. Signal and noise of 0–0 resonance at I_{ph} = 0.8 μA: a) signal in the case of a weak (1) and optimal (2) microwave field, b) noise with microwave field on, c) photocurrent noise, d) intrinsic noise of the signal channel; γ_0 = 20.5 Hz, γ = 23 Hz, F = 125, and $\Phi = 158\ \mathrm{Hz}^{-1}\ \mathrm{s}^{1/2}$.

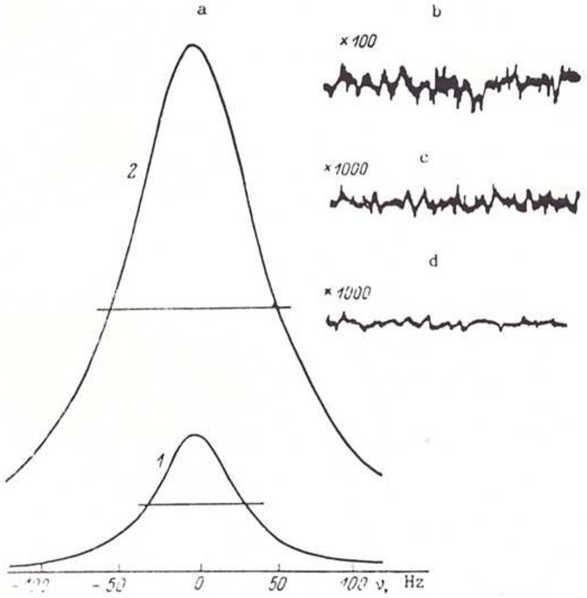

FIG. 4. Signal and noise of the 0–0 resonance at $I_{ph} = 7$ μA: $\gamma_0 = 20.5$ Hz, $\gamma = 30$ Hz, $F = 116$, and $\Phi = 1560\ \mathrm{Hz}^{-}\mathrm{s}^{1/2}$.

As an illustration, Fig. 4 shows that an increase in the pump intensity to $I_{ph} = 7$ μA ($I = 0.5$) leads to an abrupt (about 40-fold) increase in the 0–0 resonance with an attendant considerable increase (since $I < I_0$) in the maximum quality factor. On the other hand, the real quality factor $F(I)$ not only does not increase, but even decreases slightly in complete accord with (5).

4. As demonstrated above, the maximum quality factor $\Phi(I_0) \sim 10^3\ \mathrm{Hz}^{-1}\mathrm{s}^{1/2}$ of the rubidium resonance cannot be attained with the conventional technique of microwave generation on the basis of the multiplication and synthesis of the frequency of a quartz oscillator. The amplitude fluctuations, which are significant when their relative value is 10^{-5} or more, can be eliminated in a relatively simple manner by automatic control methods. On the other hand, phase fluctuations, which are ultimately determined by the quality factor of the quartz oscillators, cannot be reduced appreciably, and thus the value $F \approx 100\ \mathrm{Hz}^{-1}\mathrm{s}^{1/2}$ is close to the maximum value. The Q-factor of the rubidium resonance can be attained in full only upon passage to a more stable reference oscillator, e.g., a maser or, perhaps, a microwave oscillator with a sapphire-filled cavity.[4,5] While considering such prospects, however, we must carefully keep an eye on the priorities dictated by the specific application of the standard. The point is that attainment of the maximum quality factor $\Phi(I_0)$ requires restoration of the pump intensity to the level I_0 with a corresponding reduction of the short-term stability. If priority is given to the latter, then instead of increasing the light intensity it might prove useful to lower it further, thus sacrificing the quality of the resonance for the sake of its stability and relying on the high quality of the reference oscillator.

5. To avoid misunderstandings, we must point out that the recommended radical reduction of the pump light cannot be made in a standard device without alterations. While conserving or even increasing the quality factor, a reduction of the intensity gives rise to an abrupt decrease, also by roughly two orders of magnitude, in the magnitude of the double-resonance signal. (This behavior was a psychological barrier to the empirical implementation of these conditions.) The transition to new conditions, therefore, should be accompanied by the incorporation of an additional signal preamplifier with a fairly high input resistance, so that the photocurrent noise of the detector would dominate over the amplifier noise. Moreover, since the elimination of light shifts substantially raises the class of the device, it is necessary that all of its systems be state-of-the-art. For example, the output-frequency instability that persists when the light intensity is reduced may prove to be a trivial consequence of the nonlinearity of the microwave scanning, the magnetic-field fluctuations, etc.

6. Analysis of the resolution of a rubidium frequency discriminator with allowance for the real noise sources permits us to make the conclusion that the intensity of the pumping light must be reduced radically (by a factor of 50-100) in comparison with the values used in practice. This results in a proportional decrease in the slow frequency drifts of the 0–0 resonance, which are related to the light shifts directly or indirectly. At the present time the battle against these slow shifts is being fought by methods that compensate for the shifts introduced by the various elements of the setup by carefully matching and stabilizing their operation. The combination of this treatment with the proposed reduction of the pump light results in less stringent requirements as to the accuracy in matching and maintaining the operation of the elements while at the same time the long-term stability is increased.

In conclusion we note that the practically total elimination of light shifts by the method indicated above will make it possible to go on to a study of the next most important physical causes of slow frequency drifts of the rubidium 0–0 resonance, which are related to a change in the gas composition of the operating cell during aging.

1) Here and below width is taken to mean the full width at half maximum of the Lorentzian curve of the resonance.

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Translated by Eugene Lepa