Experimental Properties of Three-Cavity Tunnel Diode RF Oscillators

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Abstract —The properties of an oscillator-frequency stabilization scheme involving a system of three resonators used in conjunction with a tunnel diode as an active element are discussed. A theoretical description of the behavior of the oscillator is given, together with a procedure which allows one to verify the validity of the theoretical model. It is found that as the oscillator is tuned over the operating frequency range, two sets of hysteretic frequency jumps are observed, the measured position of which should completely characterize the stabilization system's parameters. Results of the frequency stability measurements on a prototype of the three-cavity oscillator are also presented which experimentally agree with the predicted stabilization properties of the system.

I. Introduction

THE USE OF high-quality factor resonators in the frequency stabilization of radio-frequency or microwave oscillators is an established technique. Since superconducting resonators became available with $Q_0 = 10^{10}-10^{11}$, the best absolute frequency stability performances have been obtained by means of techniques which lock the frequency of a free-running oscillator to a superconducting, stable cavity [1]–[3].

Among the various stabilization schemes proposed over the years, a particularly promising one has been developed in the Soviet Union [4]–[6]. In this scheme an active element, such as a tunnel diode, is stabilized in frequency by coupling it to a system of three cavities. This approach presents advantages over the use of a single cavity as a stabilizing element; for instance, it is possible to decrease the effect of the tunnel diode's bias current noise [7] by strongly coupling it to the first cavity (oscillator cavity) and at the same time one can minimize the self-oscillator noise [8], which is inversely proportional to the cavity-loaded quality factor. A single-cavity stabilized oscillator could not fulfill both requirements at the same time. The frequency stabilization scheme considered seems particularly promising in applications where a very compact secondary frequency standard is needed, such as in low-temperature experiments which require a radio-frequency local oscillator completely operating in a cryogenic environment [9].

An oscillator was built, operating at 430 MHz, to experimentally verify the validity of the theoretical analysis. This first model was not constructed for ultimate absolute frequency stability, but to allow for the possibility of varying critical parameters, such as cavity frequencies and coupling coefficients, the values of which determine the behavior of the oscillator in the theoretical model. Power spectra of fractional frequency fluctuations were measured for the system operating both as a single-cavity and as a three-cavity oscillator, and their comparison confirmed the improvement in the operation of the three-cavity system expected from the theory.

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II. Theoretical Description of the Three-Cavity Oscillator

A detailed analysis of the system was first done by Minakova and collaborators [10]–[14]. The simplest model describing this oscillator is one in which three *RLC* circuits are coupled together and are powered by an active device which has a nonlinear voltage–current characteristic (see Fig. 1). The three coupled nonlinear differential equations corresponding to this model cannot be exactly solved analytically, therefore, an approximate analytical method must be used. The full analysis of the system can be found in [9]: it makes use of the slowly varying amplitude method of Bogolyubov and Mitropolski in order to transform the set of three nonlinear differential equations into a set of six nonlinear algebraic equations for amplitudes and phases of the steady-state currents in the three circuits.

The stabilization properties of the system can be derived from these algebraic equations by solving them in terms of the oscillator frequency and of the resonators' natural frequencies. It is important to know the dependence of the oscillator frequency in terms of the oscillator cavity's (resonator 1) resonant frequency. This is because the oscillator's cavity frequency is, in first approximation, the frequency of oscillation of a one-cavity oscillator so that the properties of a single-cavity oscillator can be related to the three-cavity one through this relation. This dependence comes out to be [10]

$$\xi_1 = \eta \frac{\eta^4 + a\eta^2 + b}{\eta^4 + c\eta^2 + d} \tag{1}$$

where $\xi_1 = (\omega_1^2 - \omega_3^2)/\omega^2$, $\eta = (\omega^2 - \omega_3^2)/\omega^2$, ω is the oscillator (angular) frequency, and ω_i is the resonant (angular) frequency of the ith resonator. The constants a, b, c, and d are functions of the coupling coefficients and of the quality

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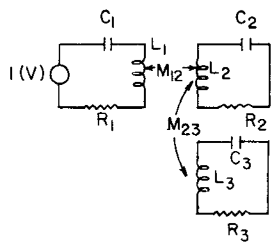

Fig. 1. Equivalent circuit of the three-cavity oscillator.

factors of the cavities

$$a = \delta_2^2 + \delta_3^2 - k_1^2 - 2k_2^2$$
$$b = \left(k_2^2 + \delta_2\delta_3\right)^2 + k_1^2\left(k_2^2 - \delta_3^2\right)$$
$$c = \delta_2^2 + \delta_3^2 - 2k_2^2$$
$$d = \left(k_2^2 + \delta_2\delta_3\right)^2 \tag{2}$$

with $\delta_2 = 1/Q_2$, $\delta_3 = 1/Q_3$, $k_1^2 = M_{12}M_{21}/L_1L_2$, and $k_2^2 = M_{23}M_{32}/L_2L_3$. M_{ij} are the mutual equivalent inductances of the resonators, L_i their self inductances. Equation (1) relates the detuning of the oscillator to the first cavity detuning under the assumption that the second and third cavities are tuned together ($\omega_2 = \omega_3$). The oscillator is always operated close to the synchronism point ($\eta = \omega_2 = \omega_3$) where the interaction of the oscillator frequency with the auxiliary cavities' frequency is important. Under this circumstance, $\xi_1 \sim \eta \ll 1$, so that

$$\left(\omega^2 - \omega_3^2\right)/\omega^2 = \left(\omega + \omega_3\right)\left(\omega - \omega_3\right)/\omega^2$$
$$\simeq 2\omega\left(\omega - \omega_3\right)/\omega^2 = 2\left(\omega - \omega_3\right)/\omega. \tag{3}$$

Therefore, (3) represents the dimensionless frequency detuning with respect to the synchronism point $\omega = \omega_1 = \omega_3$.

It should be noted that (1) is inverted since the independent variable is ξ_1: the quantity which can be physically changed is the resonant frequency of resonator 1, to which a frequency change of the oscillator follows according to (1). Equation (1) represents, in general, a multivalued function (see Fig. 2) so that for a given value of ω_1 more than one frequency of oscillation is possible. This property can also be understood in terms of the hysteretic behavior of the oscillator as the first resonator is tuned close to the synchronism point. Frequency jumps occur, which bring the oscillator frequency from one stable branch of oscillation to another (see Fig. 3). The stable branches are the ones for which the derivative $d\eta/d\xi_1$ is positive.

The description that follows highlights the operational properties of the oscillator relating them to the theoretical analysis, as they were observed and systematically measured by determining the frequency of the hysteretic jumps.

When the first cavity is detuned away from the synchronism point, the oscillator behaves like a single-cavity oscillator, in the sense that its frequency linearly follows the resonant cavity frequency. This agrees with the fact that the quantity

$$\frac{\eta^4 + a\eta^2 + b}{\eta^4 + c\eta^2 + d}$$

asymptotically converges.

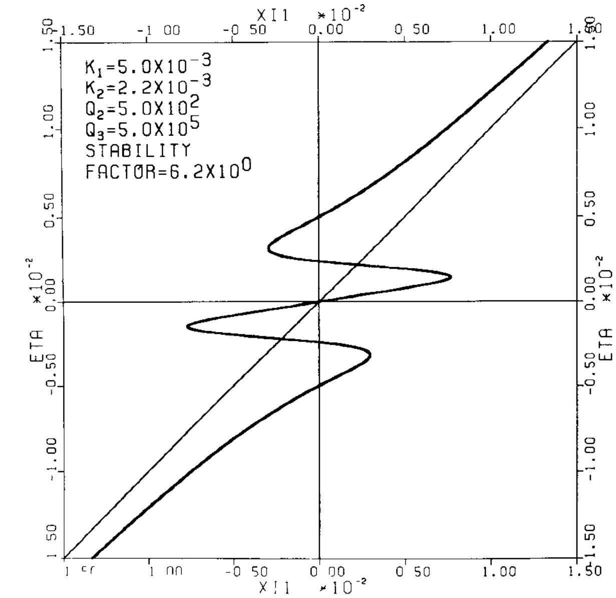

Fig. 2. Stability curve of a three-cavity oscillator.

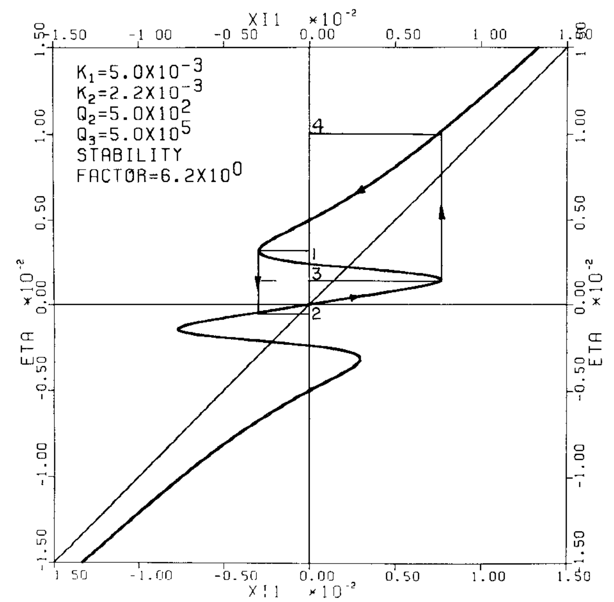

Fig. 3. Locations of the frequency jumps. The indices label the jump frequencies. A similar set of frequencies is defined for the jumps at frequencies below synchronism.

The phenomenon of frequency jumps of an oscillator coupled to an additional cavity is well known [15] and is the result of the fact that, when this coupling occurs, two separate modes of oscillation can exist. Although the modes are available simultaneously, the oscillator will lock to the one that, for the particular frequency of operation chosen, has higher stability. If the oscillator operating frequency is changed, then jumps can occur from one mode to the other, due to the fact that the mode stability is frequency dependent. The jump is hysteretic, so that the oscillator will go back to the original mode at a different frequency.

Another way of analyzing the jump phenomenon is by considering the additional resonator as having a resonance line with a certain width. As the oscillator is tuned toward the second resonator's frequency, it will interact with its resonance line. Since oscillations are forbidden at the additional resonator's frequency by stability conditions [15], the oscillator line will have to perform a frequency jump across the second resonance line.

The same stability criterion applies when the oscillator is properly coupled to two additional resonators. The only difference in this case is that the two resonators, being coupled together and tuned to the same frequency, exhibit not one, but two resonance lines. This line-splitting arises from the coupling terms of the two differential equations describing the resonators (as well as, e.g., coupled pendula) which give, as natural frequencies of oscillation $\nu_1 = \nu_0 + \Delta\nu/2$, $\nu_2 = \nu_0 - \Delta\nu/2$; ν_0 is the natural resonance frequency of both resonators when decoupled, $\Delta\nu$ is the line-splitting, proportional to the coupling coefficient.

Therefore, when an oscillator is coupled to two additional resonators and it is tuned over a frequency range containing both resonance lines, not one, but two frequency jumps will be observed across the resonance lines corresponding to the frequencies ν_1 and ν_2 described above. Each of these two jumps is hysteretic.

Since two jumps are possible, a central branch of oscillation between the frequencies ν_1 and ν_2 can be observed. In terms of Fig. 2, this branch corresponds to the modes of oscillation lying on the part of the curve going through the origin. The frequencies ν_1 and ν_2 correspond to the points where the curve crosses the 45° line. These parts of the curve have negative slope, which is equivalent to saying that the branch is unstable, since they physically represent the widths of the double lines of the coupled resonators 2 and 3: in these regions, oscillations cannot exist. The slope of the central branch at the synchronism point ($\eta = \xi_1 = 0$), the inverse of which we call the stabilization coefficient (see (8)), strongly depends on the coupling properties and on the choice of the resonators' quality factors. In general, a small Q_2 and a large Q_3 are required for large stabilization. The central branch can therefore be made very flat, thus implying that even large fluctuations in ξ_1 (and therefore in ω_1) can be reduced to small fluctuations in η (and therefore in the oscillator frequency). The above statements are not true in absolute, since an infinite stability of ω_3 is assumed. What is true is that, under proper choice of coupling and of quality factors, the oscillator will be tightly locked to the frequency of the third resonator, which can be made very stable but which, in the final analysis, is the limiting factor of any resonator-stabilized oscillator.

The existence of the central branch of oscillation can be verified by ascertaining that the oscillator frequency undergoes two separate hysteretic jumps at the edges of the branch itself. The slope of the central branch can be changed by moving the resonances ν_1 and ν_2 closer or farther apart, that is, by changing the coupling between the cavities. If the coupling is too small, though, the central branch might disappear.

The best stability performance occurs when the two resonators are coupled slightly above the critical coupling, so that the two resonances are as close together as possible (thus the central branch is as flat as possible) while still preserving their double line structure. Below critical coupling, the oscillator line will "see" the second- and third-cavity resonances as a single line and will jump clear across both, thus proving the nonexistence of a central branch.

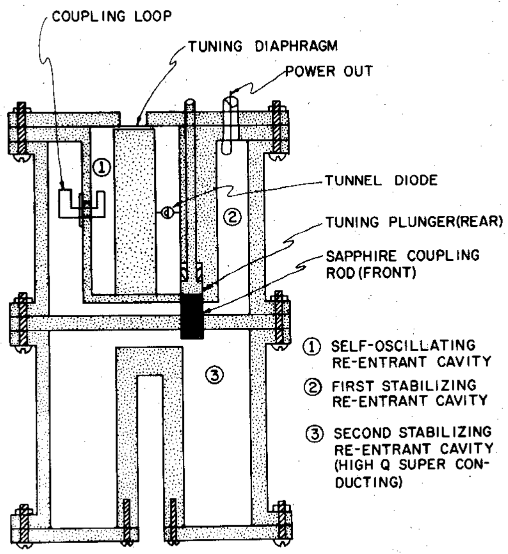

Fig. 4. Cross section of the three-cavity oscillator.

III. Experimental Apparatus and Test Procedure

A first version of the three-cavity oscillator was built in order to verify the system's features predicted by the theory and to determine which parameters play the most important roles in the stability performance of the oscillator itself.

The oscillator was built out of OFHC copper with reentrant, coaxial-type cavities resonating at ~ 430 MHz (see Fig. 4). The choice of the operating frequency was dictated by the requirement that the oscillator could be used in the future in a gravity-wave detection scheme, which makes use of an RF system in that frequency range [16].

The oscillator was designed to operate at cryogenic temperatures, to make use of superconductors to improve the Q of the third stabilizing cavity. A special high-vacuum cryostat was built for this purpose, with mechanical feedthroughs which enable one to vary the first- and second-cavity frequencies, as well as the coupling coefficients between cavities, from the room-temperature environment.

The third cavity was lead electroplated and then chemically polished, according to a procedure developed at Cal Tech [17]. It was assembled in an inert-gas glove box. Although the cavity was not optimized to achieve very high quality factors, unloaded Q's of 2–3×10^7 were routinely reached at ~ 2 K. During the operation in conjunction with the three-cavity oscillator, Q's two orders of magnitude smaller were used in order to facilitate the determination of the system's parameters. The first and second cavity had unloaded Q's typically of 2–5×10^4.

The tuning of the first cavity was accomplished through a flexible diaphragm, while the second resonator was tuned by means of a retractable post.

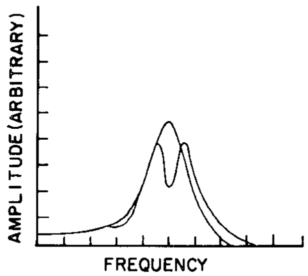

Fig. 5. Response curves for one and two coupled cavities, 1-MHz full scale.

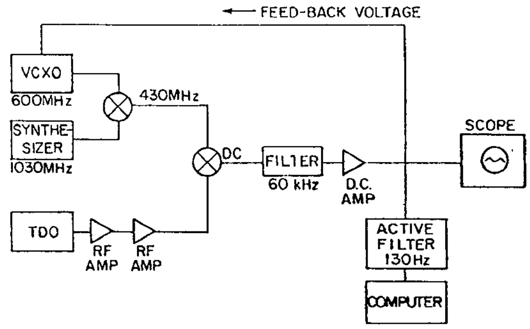

Fig. 6. Experimental setup for the measurement of frequency stability.

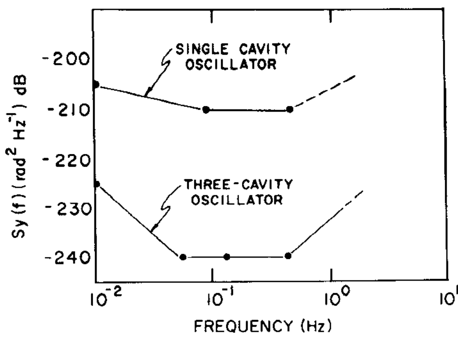

Fig. 7. Power spectrum of fractional frequency fluctuations for the single-cavity and three-cavity oscillator.

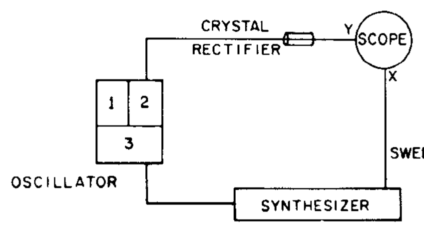

Fig. 8. Scheme for measuring frequency jumps.

The first and second cavities were coupled using a double loop which could be turned from outside the cryostat. The coupling between second and third resonators was achieved through an iris, into which a length of a sapphire cylinder could be inserted to change the amount of coupling to the desired value.

The low-power tunnel diodes used to excite the oscillator had typical peak currents in the 100-μA range and they were coupled into the oscillator cavity by means of a short, thick wire grounded to the center post.

More details on the construction of the oscillator can be found in [9].

Although the oscillator signal can be extracted through the same line that carries the dc bias to the tunnel diode, two diagnostics ports were used in cavities 2 and 3 to more easily control their tuning, and for the measurement of the coupling coefficient between them. This measurement was done in transmission by using an RF synthesizer and a crystal detector. Fig. 5 shows a graph derived from an oscilloscope trace of the transmitted power through the third cavity as a function of frequency, both for the single cavity and then for the two cavities coupled together [18].

The characterization of the oscillator performance was done by measuring the spectral density of fractional frequency fluctuations [19], through a phase-locked loop system connected to a reference oscillator (see Fig. 6). The time-dependent phase error signal in the loop was fed into a minicomputer and later processed via Fast Fourier Transform.

Power spectra were obtained for the oscillator operating both in the single-cavity mode and with the stabilizing cavities. Improvements were observed in the performance of the oscillator when the three-cavity system was used (see Fig. 7). Fig. 7 represents the smoothed power spectrum obtained from a 512-point Fourier transform over the range of 10^{-2}–1 Hz from the carrier. The decrease in the amplitude of some spectral components was more than two orders of magnitude (40 db in the spectral density), a fact which also was verified by visually inspecting the short term (10^{-3}s) amplitude of the phase-error signal on a CRT display.

Since the stabilization coefficient is a function of the coupling coefficient between the second and third cavity, stability measurements were performed with various degrees of coupling. Of particular interest was the performance in the vicinity of the critical coupling, where the central branch of Fig. 2 has the flattest slope before disappearing altogether (corresponding to the oscillator line jumping across the second- and third-cavity resonances). In this limit, the stabilization coefficient is of the order of $S \sim Q_3/Q_2$ [12]. With our system, this quantity turns out to be of the order of $S \sim 1\text{–}5 \times 10^2$, which is in agreement with the stabilization independently measured through power spectra.

Two methods were followed to verify the occurrence of frequency jumps and to measure the value of those frequencies. The first method is slightly perturbative, since it requires the use of a frequency synthesizer feeding the second and third cavity in transmission (see Fig. 8). The transmission signal is rectified and observed on the CRT. A typical pattern from this measurement is shown in Fig. 9. There, the resonances of cavities 2 and 3 can be observed (so that the system can be checked for synchronism and proper coupling), together with the mixing of the synthesizer signal with the oscillator output. The oscillator line can then be observed jumping across the resonance lines and the jump frequencies can be measured on the CRT display. This method has the disadvantage of requiring an external signal to be fed into the second and third cavities, therefore perturbing them.

The second method is very straightforward and, after proper tuning of the cavities, only requires that the oscilla-

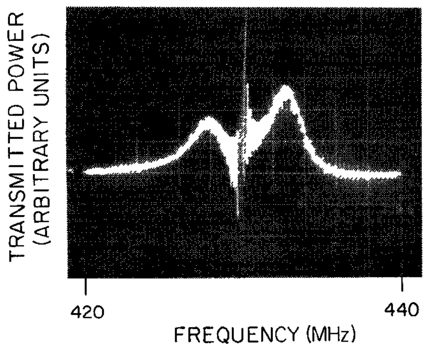

Fig. 9. Typical CRT display for frequency-jump measurements. This situation corresponds to the oscillator frequency being located on the central branch of the stability curve. The two-line separation is of the order of 5 MHz. The oscillator line is marked by the sharp spike between the two resonance lines.

tor signal be fed into a high-frequency spectrum analyzer. With this method, only the tunnel diode RF output is tapped and the other cavities are unperturbed. From the values of the pre-jump and post-jump frequencies and from their symmetry with respect to the synchronism point, it is then possible to verify whether the spectrum is operating with the cavities properly tuned. But much more information can be derived from the values of the frequency jumps in the manner described below.

IV. Connection between System Parameters and Jump Frequencies

If the parameters of the three-cavity system were independently known, then (1) would give all the information necessary to predict, within the above model, the frequency stabilization properties of the oscillator, as well as the frequencies at which the frequency jumps would occur. As we have seen, the coupling coefficients and the cavity quality factors cannot be easily measured without perturbing the system in a way that affects its performance. But since (1) describes a curve which is a unique function of the mentioned parameters, it is possible to work backward. From the equation and some values of it at some fiducial points, one can obtain the unperturbed values of quality factors and coupling coefficients. The only information necessary to retrieve the values of those parameters is the value of the oscillator frequency right before and after a set of two hysteretic jumps. As a check of the frequency alignment of the cavity, the frequencies of both sets of jumps can be measured above and below the synchronism frequency, which should lead to the same values of the parameters. This method is quite quick and effective, as long as the oscillator cavity can be tuned, although it has some problems which will be clarified below.

At the pre-jump points, the following conditions must be satisfied:

$$\left(\frac{d\xi_1}{d\eta}\right)_{\eta_1} = 0 \tag{4}$$

$$\left(\frac{d\xi_1}{d\eta}\right)_{\eta_3} = 0. \tag{5}$$

For the labeling of the jump points, see Fig. 3.

A second set of conditions has to be imposed, namely that the values of the function $\xi_1 = \xi_1(\eta)$ before and after the jumps have to be identical

$$\xi_1(\eta_1) = \xi_1(\eta_2) \tag{6}$$

$$\xi_1(\eta_3) = \xi_1(\eta_4). \tag{7}$$

The detailed derivation of the explicit form of (4)–(7) is given in [9, sec. 2.4]. We have in this way obtained a set of four independent algebraic equations which can be solved in terms of the parameters Q_2, Q_3, k_1, and k_2 which completely characterizes the frequency stabilization system. In particular, from these values the stabilization coefficient

$$S = \left.\frac{d\xi_1}{d\eta}\right|_{\eta=0} = 1 + \frac{k_1^2\left[k_2^2 - \left(1/Q_3^2\right)\right]}{\left[k_2^2 + 1/(Q_2 Q_3)\right]^2} \tag{8}$$

can be derived.

A computer program has been written to solve the set of four mildly nonlinear algebraic equations so that we have been able to compare the calculated values of the parameters with the measured ones. The equations to be solved contain, as coefficients, combinations of powers of $\eta = (\omega^2 - \omega_3^2)/\omega^2$ up to the 8th power, so that any small error in the determination of ω at the jump points, as well as any small asymmetry of the stability curve with respect to the synchronism point, rapidly propagates, greatly affecting the calculated values of the parameters. This method has given good agreement between the measured values of Q_2, k_1, k_2, and the ones determined through the frequency jump measurements. (The curve in Fig. 2 was derived by measuring the frequency jumps and finding the curve that would fit them.) The value of Q_3, which in the equations appears as its inverse [9], could not be determined accurately enough, so that it was entered as a parameter in the solution of the equations. Most of the inaccuracy of the experimental determination of Q_3 has to be ascribed to the fact that the oscillator cavity, resonating at about 400 MHz, was sharply reentrant and was tuned by adjusting the gap size. A slight hysteresis in the translation mechanism, combined with the fact that, for reentrant cavities, the frequency changes very rapidly with the gap linear dimension, accounted for the discrepancy in the determination of Q_3.

V. Conclusions

We have analyzed and experimentally verified the properties of a multiple-cavity frequency stabilization system for a RF tunnel-diode oscillator. We have found that the degree of stabilization predicted by a simple model agrees with our stability measurements. We have indicated a method by which a nonperturbative measurement of the stabilization system parameters can be performed. On the basis of the experience gained with the first model of the oscillator, a second version has been designed and built which, in order to improve the mechanical stability of the system, does not have tuning adjustments. Preliminary measurements of this oscillator, which operates at 600 MHz, indicate that frequency stabilities in the range $\Delta f/f \simeq 10^{-13}$–$10^{-14}$ could be reached in the near future.

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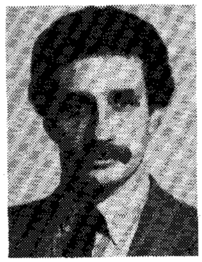

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