SUPERCONDUCTING CAVITY STABILIZED OSCILLATORS

F.F. MENDE, I.N. BONDARENKO, A.S. GNES

Physico-Technical Institute of Low Temperatures,
Ukrainian Academy of Sciences
Kharkov (USSR)

Oscillateur stabilisé à cavité supraconductrice

RESUME: *On fait un rapport sur la recherche expérimentale du système de la stabilisation de fréquence de la gamme de hyperfréquences ou le résonateur supraconducteur s'utilise en qualité de l'étalon. L'amplificateur à hyperfréquences avec le transfert d'amplification à la fréquence intermédiaire est à la base du système de l'accord automatique. L'utilisation du tel amplificateur avec le résonateur assure le transfert de fluctuations de la gamme de hyperfréquences à la gamme radioélectrique.*

L'accord automatique s'effectue à l'aide de l'oscillateur de haute stabilité de référence basse fréquence.

L'utilisation du système indiqué de la stabilisation fait possible l'obtention des signaux avec l'instabilité relative de longue durée de fréquence de l'ordre de 10^{-11} – 10^{-13} en une heure dans la gamme de hyperfréquences.

Les oscillateurs d'hyperfréquence de haute stabilité avec le raccord dans la gamme ∿100 MHz peuvent être aussi crées sur la base du système de l'autorégulation de la fréquence avec le résonateur supraconducteur.

The idea of high-stability microwave oscillator with a superconducting cavity appears to offer great promise. A very high Q-factor superconducting cavity achieving 10^{11}(1) in X-band can be used as a resonance system in high-stability oscillator and as a standard for A.F.C. systems. A series of systems with superconducting cavity stabilized microwave oscillators (2–5) hase been already realized. The output obtained can be competitive for frequency stability (10^{-10} – 10^{-12} for an hour, 10^{-12} – 10^{-13} for 10 s) with a quantum standard and reach a power much in excess of that.

This work aims to present an experimental study on the A.F.C. system for the microwave range where a superconducting cavity was used as a standard. A microwave amplifier at an intermediate frequency (6) is a principal element of the system. This amplifier together with a superconducting cavity serves to transfer the fluctuations from the microwave into rf range.

A block-diagram of stabilization system is shown in Fig. 1. The blocks are identified as follows:

1 – tuned microwave oscillator (СВЧ); 2, 3 – directional couplers or isolators; 4 – mixer; 5 – superconducting cavity; 6 – amplitude modulator; 7 – IF amplifier; 8 – phase detector; 9 – high-stability IF oscillator.

The circuit was designed to operate in the following manner: ω_r frequency output from the oscillator 1 is transferred to the mixer 4 and the modulator 6. The fluctuations from the amplifier 7 resulted in Ω frequency, which fed the modulator 6 and satisfied the relation $\omega_1 = \omega_r - \Omega$ or $\omega_2 = \omega_r + \Omega$, where ω_1 and ω_2 are frequencies, to which a superconducting cavity 5 is tuned, and Ω is a frequency within the band width of an IF amplifier. In 6 the frequency ω_r is mixed with Ω and the output the amplitude modulator is a spectrum of three frequencies $\omega_r + \Omega$, ω_r and $\omega_r - \Omega$. If a cavity is tuned to one of the sideband frequencies, $\omega_r - \Omega$, for example, this frequency passes through it and enters the mixer 4. Having been mixed with the oscillator frequency ω_r it results in a new of the form $\omega_r - \omega_r + \Omega = \Omega$.

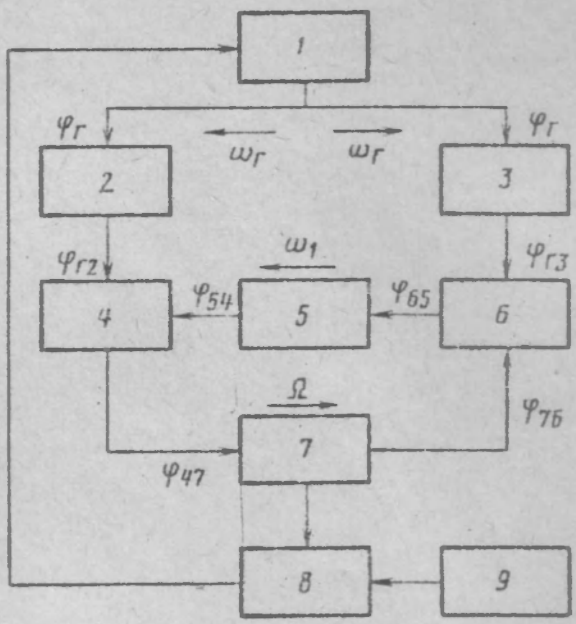

Fig. 1. A block-diagram of a stabilization system

Ω frequency being amplified in 7 again enters the modulator 6. Thus having the amplification factor high enough the system is excited. Isolators 2 and 3 are necessary to prevent a signal from the modulator from reaching the mixer, avoiding a cavity.

Taking into account the phase transfer principle we have considered the phase and frequency relations for a circuit under self-excitation conditions. The relations of the form are valid:

$$\left.\begin{aligned}
&\Delta\omega_r = \Delta\omega_1 \pm \Delta\Omega \\
&\phi_{54} \pm \phi_{47} = \phi_{r2} \\
&\phi_{65} \pm \phi_{76} = \phi_{r3} \\
&\phi_{54} - \phi_{65} = \tau_p \Delta\omega_1 \\
&\phi_{76} - \phi_{47} = \tau_\Omega \Delta\Omega
\end{aligned}\right\} \qquad (1)$$

where τ_p, τ_Ω are phase-responses slopes for the cavity and IF amplifier, respectively.

The letters φ denote the phases of the proper signals, the first index indicates the element, which a signal leaves, the second one that, which it enters.

The phase notations are clearly seen as well in the block-diagram of Fig. 1 $\Delta\omega_r, \Delta\omega_1, \Delta\Omega$ are corresponding frequency fluctuations.

When $\varphi_{r2} = \varphi_{r3}$ is satisfied and phases are excluded from equation series (1) we get:

$$\frac{\Delta\Omega}{\Delta\omega_1} = \pm \frac{\tau_p}{\tau_\Omega} \qquad (2)$$

$$\Delta\Omega = \pm \frac{1}{1+\tau_\Omega/\tau_p} \Delta\omega_r \qquad (3)$$

The plus corresponds a cavity tuned to the low sideband frequency and the minus to the upper one in the spectrum from an amplitude modulation of an oscillator 1 signal.

As it follows from Eq(2) the fluctuations of an oscillator frequency are redistributed between the fluctuations of Ω intermediate frequency and ω_1 frequency inversely to the phase-response slopes for IF amplifier and a cavity.

Eq(3) showh that the transformation coefficient of the absolute fluctuations for ω_r frequency into the fluctuation of frequency is $\frac{1}{1+\tau_\Omega/\tau_p}$.

At $\tau_p \gg \tau_\Omega$, which is the case when a superconducting cavity with a bandwidth much more narrow than that for IF amplifier is used, the transformation coefficient is found to be close oi 1, i.e. $\Delta\omega_r$ fluctuations are almost completely transformed into $\Delta\Omega$ fluctuations. This coefficient is the close to 1 the higher the Q factor of the cavity is.

If a signal from the IF amplifier feeds the phase detector 8 where it is compared to a signal from a high-stability IF oscillator, the resulting error signal can be used to tune the oscillator 1 frequency.

Using Eq(3) one can obtain a relation for a relative frequency unstability of a microwave oscillador and IF frequency:

$$\delta_\Omega = \frac{\omega_r}{\Omega} \cdot \frac{1}{1+\tau_\Omega/\tau_p} \delta_r \qquad (4).$$

where δ_r and δ_Ω are relative unstabilities of ω_r and Ω frequencies, respectively.

Eq(4) shows that at $\omega_r \gg \Omega$ the relative unstability of ω_r frequency is significantly lower than that for intermediate-frequency oscillator. This ratio of the frequencies can be usually of the order of 10^3-10^4.

Taking into account that $\Delta\Omega \approx \Delta\omega_r$ at $\tau_p \gg \tau_\Omega$ Eq(2) can be written in the form:

$$\Delta\omega_1 = \frac{\tau_\Omega}{\tau_p} \Delta\omega_r \qquad (5)$$

From Eq(5) it follows that ω_1 signal stability when a superconducting cavity is used (in this case $\frac{\omega_\Omega}{\tau_p} \sim 10^{-3} - 10^{-2}$ and is dependent upon factor of a cavity) is higher than that of the tuned oscillator which supplies the ω_r frequency.

An experimental check of the stabilization system was carried out in X-band. The scheme of the A.F.C. system is shown in Fig. 2. The notations are the same.

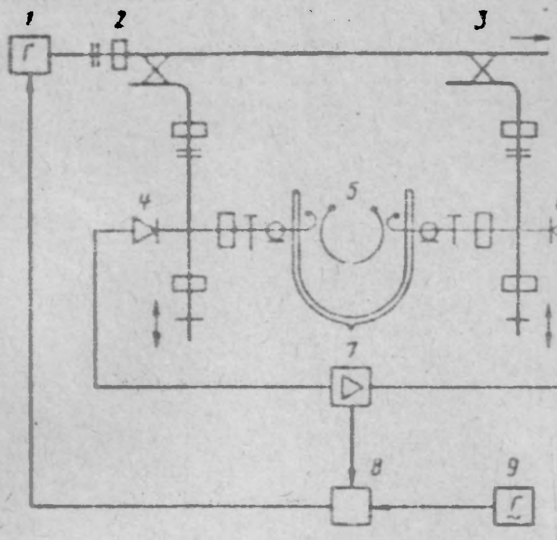

Fig. 2. A basic scheme of a stabilization system

A 60 mW reflex klystron was used as a turned oscillator. A cavity was machined from copper, subjected to mechanical and electrochemical polishing and electroplated with a lead layer from fluoborate electrolyte. A cavity was operated in the H_{011} mode, having unloaded Q factor as high as $Q_0 - 2 \cdot 10^8$ at 2^oK. It was coupled to the coaxial transmission lines, which are terminated by coupling loops from the cavity side and by the probes inserted into the glass leak-proof inlets from another side. To reduce heat transfer to a liquid helium bath the coaxial transmission lines were made from the stainless steel thin-walled tubes. An internal conductor in the coaxial transmission line was fastened by a teflon washer.

The cavity was mounted in a vacuum can and the assembly was pumped out up to $\sim 10^{-14}$ mm Hg. The vacuum can served to reduce the effects of changes in liquid helium pressure on the cavity frequency. Fig. 3 shows the scheme of the cavity assembly.

Helium bath temperature was stabilized with the accuracy of 10^{-3}°K.

Relative frequency unstability was determined by beat frequency measurements for two klystron oscillators being stabilized with the above circuit. The effect of vibrations on beat frequency stability was prevented by fixing the both oscillators to the same massive platform. Frequency unstability effect of the low-frequency oscillator was removed by using it simultaneously in both autotuned systems.

A low-frequency quartz-crystal oscillator used was operated at 10 MHz having relative frequency unstability about $\sim 5 \cdot 10^{-8}$ for an hour. To amplify the intermediate frequencies we used resonant amplifiers with a gain as high as 60 dB.

Relative frequency unstability in a klystron oscillator determined as is shown above was $\delta_r \sim 10^{-12}$ for an hour.

Using the directional couplers as isolators enabled us to reduce the microwave power loss due to stabilization to 1—2 mW value.

It should be noted that in accordance with (5) frequency stability of a signal from a cavity is 10^2-10^3 times higher than that of the tuned

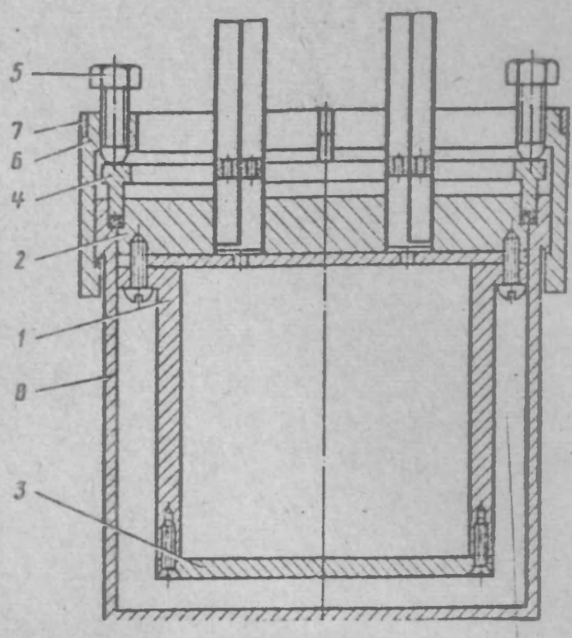

Fig. 3. The asembly of a superconducting cavity: 1 — cavity case; 2 — vacuum can lid; 3 — lower lid of cavity; 4 — seal-ring; 5 — bolts; 6 — semirings with butt-shaped lugs; 7 — ring to fix the semirings; 8 — case of a vacuum can

oscillator Thus, the power output of the resulted oscillations is not high, but it can be improved by increasing the cavity coupling, which in turn results in the reduced Q-factor, a stability gain, however, would be of the order of magnitude of 1—2 corresponding to relative frequency unstability $\sim 10^{-13} - 10^{-14}$.

A further decrease in relative frequency unstability is probably due to temperature stability of a helium bath, which is increased, and to higher Q-factors of the superconducting cavities used. In this connection the use of Nb cavities seems to be promising (1).

A stabilization system considered can be used in the design of a microwave high-stability oscillator tuned to a desired frequency.

Two techniques were employed to tune to a frequency. The first technique was based on using a tuned superconducting cavity instead of an untuned one, all the rest elements remained unchanged. The tuned cavity has a lower Q-factor and worse standard qualities than the untuned one due to a tuning element and a special mechanism to more it included the system, but it enables us to reach relative frequency unstability about $\sim 10^{-10}$ while tuning over a few decades of MHz.

When the second technique is used very high Q-factors and standard properties of the untuned superconducting cavity are unchanged. To tune to a frequency one must substitute a wideband amplifier for the IF amplifier, and a tuned oscillator is preferred to low-frequency oscillator (7). Using a wideband amplifier one can obtain while tuning the oscillator a series of excitations in a circuit: mixer 4 – amplifer 7 – modulator 6 – cavity 5 (Fig. 1) at a distance of $\Delta\Omega = \frac{2\pi}{\tau_3}$, where τ_3 is delay time of a wide-band amplifier. At any excitation autotuning for a microwave oscillator can be realized by means of low frequency tuned oscillator. The excitation shift to the other frequencies is achieved by a phase change of the signal travelling from a tuned source to a modulator.

All the indicated changes in the circuit make it possible to obtain relative frequency unstability about $\sim 5 \cdot 10^{-10}$ for an hour in 100 MHz tuning band with Q-factor of superconducting cavity of 10^7. The tuning range in this case is dependent only on the band-width of a wide-band amplifier and the tuning range of the low-frequency oscillator.

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