PAPER Special Issue on Microwave and Millimeter-Wave Technology for Advanced Functions and Size-Reductions

Noise Temperature of Active Feedback Resonator (AFR)

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SUMMARY An active feedback resonator (AFR) is a kind of circuit which functions as a high unloaded Q resonator. The AFR employs an active feedback loop which compensates for the energy loss of a conventional microwave resonator. Owing to an active element in the AFR, thermal noise should be taken into account when designing the AFR. In order to simplify a circuit design using the AFR we introduced noise temperature (T_n) for the AFR. In addition, we describe the AFR design which gives minimum noise temperature. Finally, the noise temperature, measured in an AFR as a band elimination filter, is compared with the theoretical value to evaluate the AFR.

key words: *active feedback resonator, AFR, microwave resonator, unloaded Q, thermal noise, noise temperature*

1. Introduction

When a microwave resonator is miniaturized, unloaded Q generally decreases in proportion to the cube root of its volume.(1) This is mainly caused by the Joule loss of a microwave electromagnetic field in a conductive shield. An active feedback resonator (AFR)(2),(3) has been proposed as a means to compensate for energy loss in the resonator and to produce a high unloaded Q resonator. In an AFR, a feedback loop is added for control and gain in the unloaded Q. However, thermal noise, which is negligible in a conventional passive resonator, must be taken into account. In particular, it is very complicated to evaluate NF when the AFR is applied to a multi-pole BEF(4) and time is required even when a circuit simulator is used. The complexity of the circuit structure of the AFR has been the cause of this problem.

In this paper, we will show that an AFR can be treated in the same manner as a passive resonator with high unloaded Q, in which unloaded Q is Q_0 and the temperature is T_n, by introducing noise temperature T_n to the AFR. Then we will show the noise minimum method(5) which minimizes T_n. Finally, we will show the measurement of noise temperature in a single-pole AFR BEF model, and will compare the theory with experimental results.

Manuscript received November 16, 1992.
Manuscript revised February 10, 1993.

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2. Circuit Structure of AFR

As shown in Fig. 1, an active feedback resonator (AFR) consists of a feedback loop and a conventional passive resonator.

The coupling Q of the input- and output-ports of the active feedback loop relative to the resonator are Q_{e1} and Q_{e2}. Resonance energy is positively fed back after being amplified by the low noise amplifier.

As a result, the AFR compensates for the power loss in the resonator, and gains the equivalent unloaded Q in the resonator. Additionally, it can be kept small because only the volume of the amplifier is added.

Here, we will derive the relationship between Q (Q_{00}), the initial unloaded Q, and Q (Q_0), the unloaded Q in the AFR, following analysis of AFR equivalent circuits.

The S parameter of the two terminal circuit illustrated in Fig. 2 is shown by

$$S=\begin{pmatrix} -1+\dfrac{2Q(\omega)}{Q_{e1}} & \dfrac{2Q(\omega)}{\sqrt{Q_{e1}Q_{e2}}} \\ \dfrac{2Q(\omega)}{\sqrt{Q_{e1}Q_{e2}}} & -1+\dfrac{2Q(\omega)}{Q_{e2}} \end{pmatrix}, \tag{1}$$

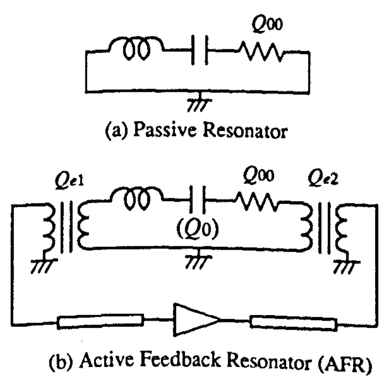

Fig. 1 Circuit structure of AFR.

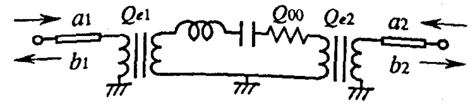

Fig. 2 Two terminal resonance circuit.

where

$$\frac{1}{Q(\omega)} \equiv \frac{1}{Q_{00}} + \frac{1}{Q_{e1}} + \frac{1}{Q_{e2}} + j\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right). \quad (2)$$

From Eq. (1), as shown in Fig. 2, the amplitudes of microwaves, a_1, a_2, b_1, b_2, which pass through the input- and output-ports, can be derived to

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = S \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}. \quad (3)$$

Similarly, the following equation can be derived in the AFR:

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = G \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}. \quad (4)$$

where G is the S parameter of the low noise amplifier.

Stable resonance can be achieved when a hypothetical negative resistance $(-Q_0)$ is introduced as shown in Fig. 3.

In this case, $Q(\omega)$ in (2) can be replaced by $Q'(\omega)$ which is expressed by

$$\frac{1}{Q'(\omega)} = -\frac{1}{Q_0} + \frac{1}{Q(\omega)}. \quad (5)$$

From such a substitution in (1), a solution other than a zero vector which satisfies (3) and (4) simultaneously can be obtained, resulting in

$$\det(SG - E) = 0. \quad (6)$$

where E is a unit matrix.

For example, when an ideal amplifier, in which the S parameter is expressed by

$$G = \begin{pmatrix} 0 & 0 \\ \sqrt{G} & 0 \end{pmatrix} \quad (7)$$

is considered as an example, combining (1), (6) and (7) yields

$$-\frac{1}{Q_0} + \frac{1}{Q_{00}} + \frac{1}{Q_{e1}} + \frac{1}{Q_{e2}} - 2\sqrt{\frac{G}{Q_{e1}Q_{e2}}} + j\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) = 0. \quad (8)$$

The real part of (8) gives an equation which the unloaded Q of the AFR (Q_0) satisfies, and the imaginary part gives the resonance frequency of the AFR (ω_r). When the phase of the active feedback loop is an integer multiple of 2π, the following results can be derived

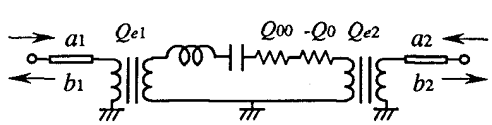

Fig. 3 Two terminal resonance circuit with negative resistance.

$$\frac{1}{Q_0} = \frac{1}{Q_{00}} + \frac{1}{Q_{e1}} + \frac{1}{Q_{e2}} - 2\sqrt{\frac{G}{Q_{e1}Q_{e2}}}, \quad (9)$$

$$\omega_r = \omega_0. \quad (10)$$

In a practical situation, the electrical length of the active feedback loop can be deviated by $\delta\theta$ from the design value caused by thermal fluctuations. In this case, the transmission coefficient of the amplifier in (8) which is transformed as

$$\sqrt{G} \rightarrow \sqrt{G}\, e^{j\delta\theta} \quad (11)$$

gives the deviations of both the unloaded Q and the resonance frequency expressed by

$$\frac{1}{Q_0} = \frac{1}{Q_{00}} + \frac{1}{Q_{e1}} + \frac{1}{Q_{e2}} - 2\sqrt{\frac{G}{Q_{e1}Q_{e2}}} \cos\delta\theta, \quad (12)$$

$$\omega_r = \omega_0 + \omega_0\sqrt{\frac{G}{Q_{e1}Q_{e2}}} \sin\delta\theta. \quad (13)$$

3. Noise Temperature of AFR

We showed that unloaded Q of a resonator can be controlled by the AFR circuit structure. In general, however, noise energy which is stored in the AFR tends to increase due to thermal noise of the amplifier. Therefore, NF should be taken into account as one of the most important factors when a filter is designed using an AFR. In order to show to what extent the noise energy stored in an AFR increases, we introduced a noise temperature T_n into the AFR as a parameter characteristic of the resonator. This parameter makes it possible to design noise in the AFR regardless of the filter design.

In order to define the noise temperature of the AFR, we assume that the AFR is equal to a passive resonator in which the temperature is T_n and the unloaded Q is Q_0. With this assumption, the noise energy which is stored in each resonator has the same value.

Initially, we consider the noise energy which is stored in the passive resonator with a temperature of T_n.

This calculation is simplified by an equivalent

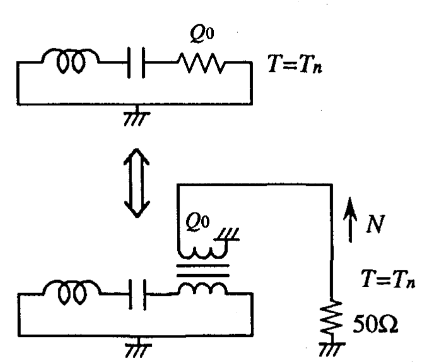

Fig. 4 Equivalent circuit transformation of a resonator.

circuit transformation which is illustrated in Fig. 4. Figure 4 shows that the noise power, which is generated from 50 Ω of resistance at a temperature of T_n, enters the resonator after passing an ideal transformer whose coupling Q is Q_0. According to this model, the noise energy which is stored in the resonator can be derived to

$$W_S^{(N)}=\frac{4Q_0N}{\omega_0}. \tag{14}$$

Similarly, the noise energy which is stored in the AFR is calculated depending on an equivalent-circuit transformation which is illustrated in Fig. 5.

The amplitudes of noise, (a_0, a_1, a_2) and (b_0, b_1, b_2), which pass every port in Fig. 5 back and forth, satisfy the simultaneous Eqs. (15) and (16) in the equilibrium state with respect to thermal noise:

$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \end{pmatrix}=\begin{pmatrix} -1+\frac{2Q_L}{Q_{00}} & \frac{2Q_L}{\sqrt{Q_{00}Q_{e1}}} & \frac{2Q_L}{\sqrt{Q_{00}Q_{00}}} \\ \frac{2Q_L}{\sqrt{Q_{e1}Q_{00}}} & -1+\frac{2Q_L}{Q_{e1}} & \frac{2Q_L}{\sqrt{Q_{e1}Q_{e2}}} \\ \frac{2Q_L}{\sqrt{Q_{e2}Q_{00}}} & \frac{2Q_L}{\sqrt{Q_{e2}Q_{e1}}} & -1+\frac{2Q_L}{Q_{e2}} \end{pmatrix}\begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix}, \tag{15}$$

$$\begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix}=\begin{pmatrix} 0 \\ 0 \\ \sqrt{G}\,b_1 \end{pmatrix}+\begin{pmatrix} n_0 \\ n_b \\ n_a \end{pmatrix}, \tag{16}$$

where Q_L in (15) is the loaded Q of the resonator, and satisfies

$$\frac{1}{Q_L}=\frac{1}{Q_{00}}+\frac{1}{Q_{e1}}+\frac{1}{Q_{e2}}. \tag{17}$$

n_0, n_b, and n_a are the amplitudes of the noise source which are unrelated to one another, and can be transformed as in (18) when the noise power is calculated:

$$N_0=|n_0|^2,\ N_b=|n_b|^2,\ N_a=|n_a|^2. \tag{18}$$

The noise energy which is stored in the AFR can be calculated as follows using the noise amplitudes (a_0, a_1, a_2) which enter the resonator:

$$W_S^{(N)}=\frac{4Q_0^2}{\omega_0}\left|\frac{a_0}{\sqrt{Q_{00}}}+\frac{a_1}{\sqrt{Q_{e1}}}+\frac{a_2}{\sqrt{Q_{e2}}}\right|^2. \tag{19}$$

Substituting the solutions of (15) and (16) into (19) yields

$$W_S^{(N)}=\frac{4Q_0^2}{\omega_0}\left\{\frac{N_0}{Q_{00}}+\left(\sqrt{\frac{1}{Q_{e1}}}-\sqrt{\frac{G}{Q_{e2}}}\right)^2 N_b+\frac{N_a}{Q_{e2}}\right\}. \tag{20}$$

The condition in which the noise energy in (14) and (20) is equal leads to

$$\frac{N}{Q_0}=\frac{N_0}{Q_{00}}+\left(\sqrt{\frac{1}{Q_{e1}}}-\sqrt{\frac{G}{Q_{e2}}}\right)^2 N_b+\frac{N_a}{Q_{e2}} \tag{21}$$

where

$$\begin{aligned} N&=kT_nB,\\ N_0&=kT_0B,\\ N_b&=kT_bB,\\ N_a&=GkT_aB. \end{aligned} \tag{22}$$

Using (22), (21) can be transformed to the following expression depending on temperature; an equation which indicates the temperature of the passive resonator, T_n:

$$T_n\equiv\frac{Q_0}{Q_{00}}T_0+Q_0\left(\sqrt{\frac{1}{Q_{e1}}}-\sqrt{\frac{G}{Q_{e2}}}\right)^2 T_b+\frac{Q_0}{Q_{e2}}GT_a. \tag{23}$$

We define this equation as that for the noise temperature of the AFR.

4. Minimum Noise Method

As an electrical design method of an AFR, we can minimize the noise temperature in (23) by combining Q_{e1} and Q_{e2} which satisfy the conditions in (9), provided that Q_0, Q_{00}, and G are given previously. The minimum noise condition gives an extreme value problem of (23) in which (9) is satisfied as a necessary condition, resulting the following simple relationship:

$$\frac{1}{Q_{e1}}=\frac{G}{Q_{e2}}. \tag{24}$$

Equation (24) is not only the maximum condition for Q_{e2} but also the minimum condition for T_n because the second term and the third term in (23) are zero and

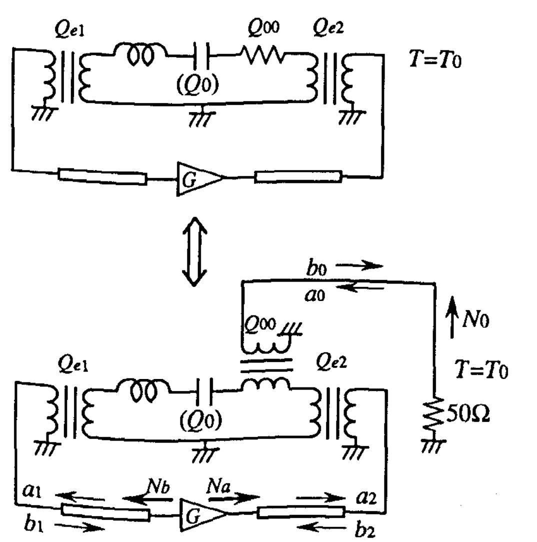

Fig. 5 Equivalent circuit transformation of an AFR.

minimized, respectively. By substituting (24) into (9), the coupling Q of the AFR can be expressed as the following equations:

$$Q_{e1}=\left\{\frac{G}{G-1}\left(\frac{1}{Q_{00}}-\frac{1}{Q_0}\right)\right\}^{-1}, \tag{25}$$

$$Q_{e2}=\left\{\frac{1}{G-1}\left(\frac{1}{Q_{00}}-\frac{1}{Q_0}\right)\right\}^{-1}. \tag{26}$$

Substituting these Q_{e1} and Q_{e2} values in (23) yields the minimum noise temperature which is defined by

$$T_n|_{\min}=\frac{Q_0}{Q_{00}}T_0+\frac{G}{G-1}\left(\frac{Q_0}{Q_{00}}-1\right)T_a. \tag{27}$$

The first term in the right side of (27) represents noise temperature which rises due to apparent gain in the unloaded Q, while the noise power, generated from internal resistance in the resonator, is unchanged in the AFR. The second term represents the minimum value with respect to the noise from the amplifier. The first factor of the second term here can be neglected if the gain of the amplifier is far larger than 1.

Here, we define the rate of increase of noise temperature using the following equations which are transformed from (27):

$$\theta\equiv\left(T_n-\frac{Q_0}{Q_{00}}T_0\right)\Big/\left(\frac{Q_0}{Q_{00}}-1\right)T_a$$

$$=\frac{1}{T_a}\left(\frac{Q_{00}}{Q_0-Q_{00}}T_n-\frac{Q_0}{Q_0-Q_{00}}T_0\right), \tag{28}$$

$$\theta_{\min}=\frac{G}{G-1}. \tag{29}$$

The smaller the difference between θ obtained from (28) and the minimum value ($\theta_{\min}$), the better the design of the AFR in terms of noise.

Figure 6 shows how θ changes depending on Q_{e2}/GQ_{e1}.

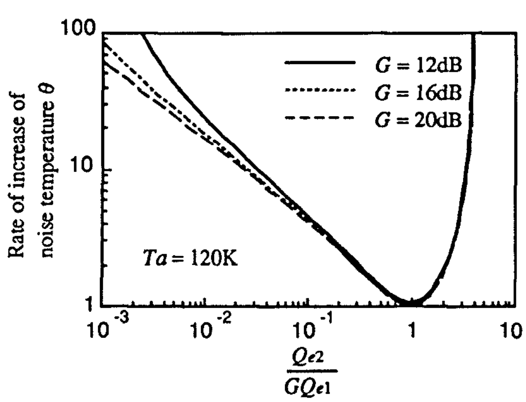

Fig. 6 The rate of increase of noise temperature of an AFR.

5. Design of Single-Pole AFR BEF and Its Characteristics

In the previous discussion, we showed that an AFR is equivalent to a resonator with high unloaded Q at high temperature. When a circuit device is designed using an AFR, this concept is useful, and facilitates calculations using a circuit simulator. For example, the frequency characteristics of insertion loss (IL) and noise figure (NF) can easily be derived from analysis of a passive resonator like this.[6]

The following equations (30) and (31) show the results of this analysis. The equivalent circuit of an AFR BEF and the characteristic curves with respect to IL and NF are shown in Figs. 7 and 8, respectively.

$$\mathrm{IL}(\omega)=10\log\left(1+\frac{\dfrac{2}{Q_0Q_e}+\left(\dfrac{1}{Q_e}\right)^2}{\left(\dfrac{1}{Q_0}\right)^2+\left(\dfrac{\omega}{\omega_0}-\dfrac{\omega_0}{\omega}\right)^2}\right) \tag{30}$$

$$\mathrm{NF}(\omega)=10\log\left(1+\frac{\dfrac{2}{Q_0Q_e}\cdot\dfrac{T_n}{T_0}}{\left(\dfrac{1}{Q_0}\right)^2+\left(\dfrac{\omega}{\omega_0}-\dfrac{\omega_0}{\omega}\right)^2}\right) \tag{31}$$

As can be seen in Fig. 8, NF has a maximum at the resonance point and approaches 0 dB as the frequency moves away from the resonance point. These characteristics imply that NF in the transmission region is small which is very favorable when an AFR is applied

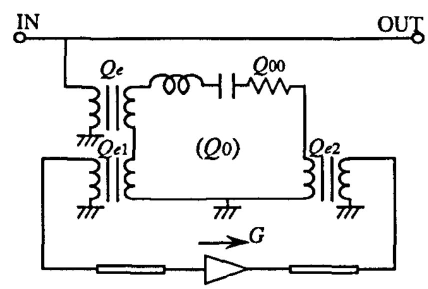

Fig. 7 Equivalent circuit of an AFR BEF.

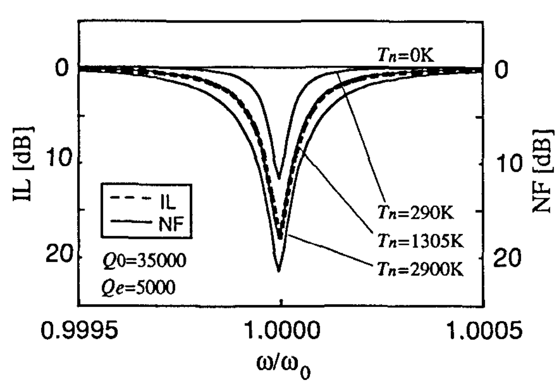

Fig. 8 IL and NF characteristics of an AFR BEF.

to a BEF.

However, NF increases as the noise temperature rises. Therefore, it is necessary to know what degree of T_n meets the design target. In this respect, we consider the critical noise temperature where the insertion loss coincides with the noise factor. This condition implies that both the input noise and the output noise are at the same level. Combining (30) and (31), we obtained the following equation which is independent of frequency:

$$T_n|_c=\left(1+\frac{Q_0}{2Q_e}\right)T_0 \tag{32}$$

Equation (32) shows that the critical noise temperature depends on the design of a filter: The critical noise temperature rises as the unloaded Q of the AFR becomes larger than the coupling Q of the filter.

NF can be neglected when an AFR BEF is designed below the critical noise temperature. Above the critical noise temperature, however, NF in the transmission region has to be taken into account to evaluate the noise temperature.

6. Measurement of Noise Temperature

In this section, we show several experimental results using an AFR BEF and compare them with the theoretical analysis which has been discussed above.

In our experiment, a TM_{110}-mode dielectric resonator(7)–(10) which is shown in Fig. 9 was used as an AFR.

6.1 Noise Temperature Measurement System and Formula

Figure 10 shows the equivalent circuit of the four terminal resonator which was used for the AFR BEF.

Coupling Q (Q_e, Q_{e1}, Q_{e2}) and the unloaded Q(Q_{00}) of the four terminal resonator can accurately be obtained by measuring the transmission S parameter at a resonance frequency:

$$Q_e=\frac{Q_L}{1-|S_{21}|},$$

$$Q_{e1}=\frac{2Q_L}{|S_{43}|}\frac{|S_{41}|}{|S_{31}|},$$

$$Q_{e2}=\frac{2Q_L}{|S_{43}|}\frac{|S_{31}|}{|S_{41}|},$$

$$Q_{00}=\frac{2Q_L}{|S_{43}|}\left(\frac{2|S_{21}|}{|S_{43}|}-\frac{|S_{31}|}{|S_{41}|}-\frac{|S_{41}|}{|S_{31}|}\right)^{-1}, \tag{33}$$

where Q_L is the loaded Q of the four terminal resonator.

Figure 11 shows a schematic diagram of the system for noise temperature measurement. Isolators were inserted before and after the amplifier in the active feedback loop in order to achieve impedance matching with input and output load. This matching enables the amplifier to operate at 50 Ω, and to form a circuit in accordance with the circuit model for analysis.

The output noise (N_{out}) measured by the spectrum analyzer, which is shown in Fig. 11, consists of three types of noise power; noise power of the AFR, noise power of the terminal load (50 Ω) at the input terminal ($N_{in}=N_0$) and noise power which enters from measurement devices into the sample ($N_{sys}=N_0$). On taking the definitions of IL and NF into account, Eqs. (30) and (31) are reduced to N_{out} at resonance which is expressed by

$$N_{out}=\frac{\left(\frac{1}{Q_0}\right)^2 N_{in}+\left(\frac{1}{Q_e}\right)^2 N_{sys}+\frac{2}{Q_0Q_e}\frac{T_n}{T_0}N_0}{\left(\frac{1}{Q_0}+\frac{1}{Q_e}\right)^2}. \tag{34}$$

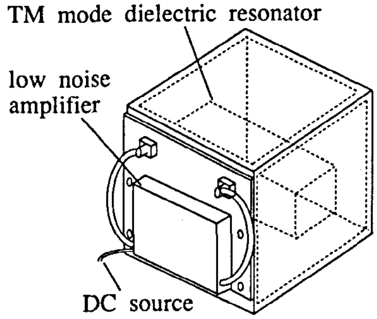

Fig. 9 Structure of an AFR using a TM_{110} mode dielectric resonator.

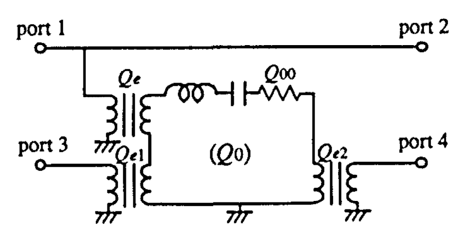

Fig. 10 Equivalent circuit of the four terminal resonance circuit.

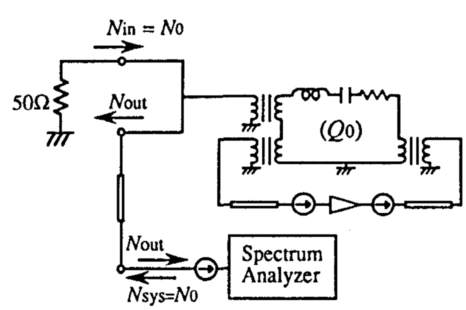

Fig. 11 Noise temperature measurement system for an AFR BEF.

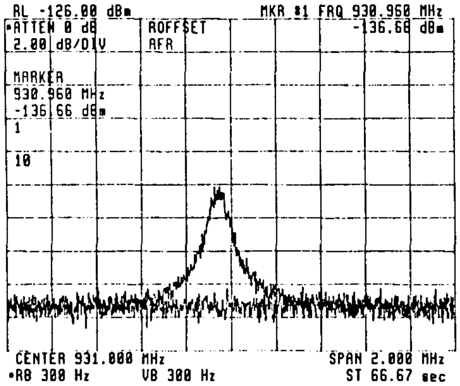

Fig. 12 Experimental results on noise power.

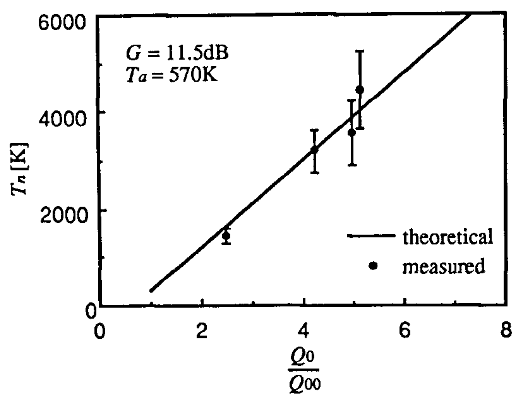

Fig. 13 Noise temperature of an AFR vs. unloaded Q.

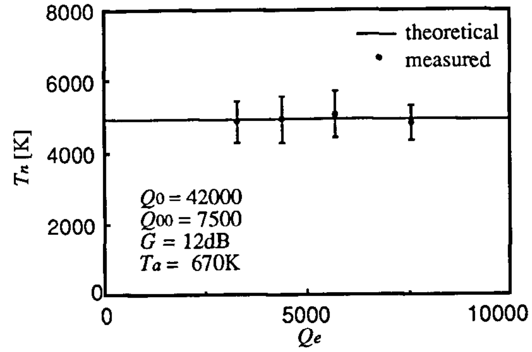

Fig. 14 Noise temperature of an AFR vs. coupling Q.

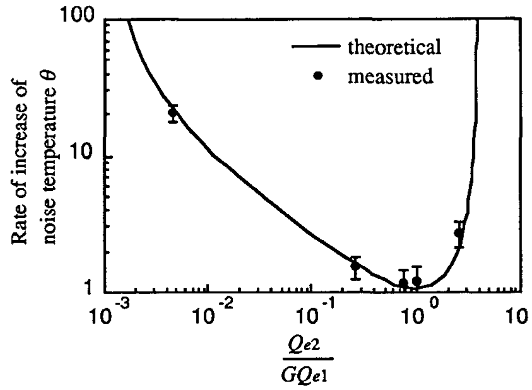

Fig. 15 Measurement of the rate of increase of noise temperature.

Assuming both N_{in} and N_{sys} are equal to white noise power N_0, (34) can be solved for T_n/T_0 to give the following formula for noise temperature measurement:

$$\frac{T_n}{T_0} = 1 + \frac{Q_e}{2Q_0}\left(1 + \frac{Q_0}{Q_e}\right)^2\left(\frac{N_{out}}{N_0} - 1\right). \tag{35}$$

Figure 12 shows one of the results of the noise power measurement.

N_{out}/N_0 can be obtained by measuring the NF of measurement devices, and the difference between the maximum noise and the white noise at the resonance point. Then the noise temperature can be obtained using (35).

6.2 Experimental Results

The minimum noise method gives a linear relationship, which is expressed by (36), between the noise temperature and unloaded Q of an AFR:

$$\left.\frac{T_n}{T_0}\right|_{min} = 1 + \left(1 + \frac{G}{G-1}\frac{T_a}{T_0}\right)\left(\frac{Q_0}{Q_{00}} - 1\right). \tag{36}$$

The experimental results which verify the linearity is shown in Fig. 13.

Figure 14 shows the noise temperature of the AFR which was designed based on the minimum noise condition, and the experimental result of the coupling Q for the AFR BEF. It can be seen that the noise temperature is independent of the coupling Q of the filter and is the parameter characteristic of the AFR.

Figure 15 shows the experimental results concerning the rate of increase of noise temperature (θ) of the AFR. It can be seen that θ has a minimum at the point where the noise minimum condition is satisfied and that (24) is valid. In addition, θ increases in accordance with the theory at points other than the minimum noise condition.

7. Conclusion

Theoretical equations with respect to unloaded Q were derived depending on AFR circuit structures. We then introduced noise temperature in order to facilitate the design of a circuit device using an AFR and showed that the noise temperature is valid in an evaluation of the noise characteristics of a resonator. Finally, we showed the design conditions which minimize noise temperature, and derived a formula and the minimum noise temperature for the AFR based on this condition.

The experimental results were in good agreement with the theory. These results are accounted for by the error range which is calculated from the read error of the noise power. In practical measurements, we confirmed that the noise temperature depends on the unloaded Q, that the noise temperature is a parameter characteristic of the resonator and that the minimum noise condition is valid.

Further studies regarding the dependence of an AFR on temperature and electric power, and distortion characteristics of an AFR will be carried out.

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