NOISE DESIGN OF ACTIVE FEEDBACK RESONATOR BEF

Youhei Ishikawa, Sadao Yamashita and Seiji Hidaka

Murata Manufacturing Company Limited
Microwave Components Development Department I
26–10, 2–chome, Tenjin, Nagaokakyo–shi, Kyoto 617, Japan

ABSTRACT

Active feedback resonator (AFR) filters are available to use design techniques for conventional passive microwave filters by introducing noise temperature of resonator. The noise figure (NF) of AFR filters can be analytically designed by utilizing noise temperature. In this paper, a three–pole AFR band elimination filter (BEF) is designed to evaluate NF value. The observed results agree well with the theoretical values.

I. INTRODUCTION

It is known that for small–sized microwave resonators the unloaded Q will generally deteriorate in proportion to the cube root of its volume. The deterioration mainly originates from the Joule loss of microwave electromagnetic field in a conductive shield. Several approaches using active elements or negative resistance have been introduced to recover low–Q characteristic[1]. An active feedback resonator (AFR)[2] has been proposed as a device to realize a high–Q resonator compensating for the energy loss of a passive resonator.

An AFR is a kind of resonance circuit with high–Q characteristics. In the AFR, the resonator energy loss is compensated by an active feedback loop connected to the conventional microwave resonator. Owing to an active element in the AFR, thermal noise should be taken into account when designing the AFR. For this reason, the optimum noise design is an important problem for AFR design. However, no suitable circuit and noise design techniques have been known for the AFR filter design. Due to the complexity of the AFR circuit, complicated procedures of noise analysis are required for evaluation of NF value.

According to circuit theory, an AFR can be expressed as a circuit equivalent to a passive resonator by introducing the noise temperature of the AFR[3]. It enables quantitative treatment of the thermal noise as well as simple analysis of AFR, so that AFR filter design can use design techniques for the conventional passive resonator filter. The NF value of a filter can also be evaluated by measuring the noise temperatures of AFRs.

First, the equivalent circuit and the noise temperature of AFR are described. Second, the analysis and the noise design are discussed for the AFR BEF. Finally, the NF value of a three–pole AFR BEF is observed and compared with the theoretical value.

II. NOISE TEMPERATURE OF AFR

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

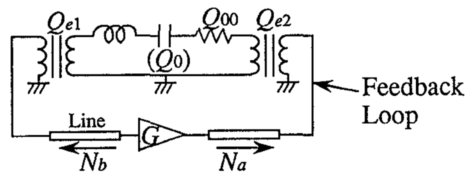

Fig. 1 Equivalent Circuit of the AFR

The low–noise amplifier shown in Fig. 1 will ideally amplify only the incident power with a gain of G. The parameters Q_0 and Q_{00} denote the unloaded Q with and without active feedback loop, respectively. The input and output ports of the active feedback loop are connected to the resonator with external Q's of Q_{e1} and Q_{e2}.

The 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 enhances the equivalent unloaded Q in the resonator.

When the phase of active feedback loop equals an integer times 2π, the resonance frequency of AFR is kept at the initial value and the unloaded Q is expressed by the following design formula[3]:

$$\frac{1}{Q_0} = \frac{1}{Q_{00}} + \frac{1}{Q_{e1}} + \frac{1}{Q_{e2}} - 2\sqrt{\frac{G}{Q_{e1}Q_{e2}}} \quad . \tag{1}$$

Introducing the noise temperature T_n, AFR shown in Fig. 1 can be expressed as the high–Q passive resonator with the temperature T_n shown in Fig. 2.

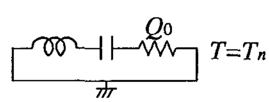

Fig. 2 Equivalent Conversion of AFR Circuit

The symbols N_a and N_b shown in Fig. 1 denote the noise power generated at the output and the input sides of the low-noise amplifier. Here, we will define the noise temperature T_a and T_b by the following equations:

$$N_a \equiv GkT_aB, \quad N_b \equiv kT_bB, \tag{2}$$

where k is the Boltzmann constant and B the bandwidth. Utilizing the noise temperatures defined by (2) and the white noise temperature T_0 (=290K), the noise temperature of AFR shown in Fig. 2 is defined by the following equations:

$$T_n \equiv \frac{Q_0}{Q_{00}}T_0 + \frac{Q_0}{Q_{e2}}GT_a + Q_0\left(\sqrt{\frac{1}{Q_{e1}}} - \sqrt{\frac{G}{Q_{e2}}}\right)^2 T_b. \tag{3}$$

If the parameters Q_0, Q_{00} and G are specified in the electrical design of AFR, the optimum design minimizing the noise temperature (3) can be performed by the combination of Q_{e1} and Q_{e2} that satisfy the condition (1). This optimum design is an extreme value problem of (3) in which (1) is satisfied as a necessary condition, resulting in the following simple relation:

$$\frac{1}{Q_{e1}} = \frac{G}{Q_{e2}}. \tag{4}$$

The minimum noise temperature is expressed by

$$T_n\big|_{\min} = \frac{Q_0}{Q_{00}}T_0 + \frac{G}{G-1}\left(\frac{Q_0}{Q_{00}} - 1\right)T_a. \tag{5}$$

The first term on the right side of (5) represents the risen noise temperature of the interior resistance in proportion to the enhancement of unloaded Q, while the second term represents the minimum noise contribution from the amplifier.

III. NOISE DESIGN OF AFR BEF

The following describes the noise design of a AFR BEF. An equivalent circuit of AFR BEF is shown in Fig. 3.

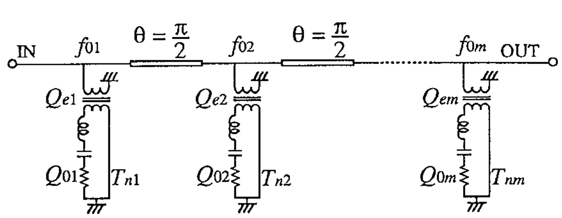

Fig. 3 Equivalent Circuit of AFR BEF

In Fig. 3, f_{0l}, Q_{el}, Q_{0l} and T_{nl} (l=1, 2, ..., m) denote the resonance frequency, the external Q, the unloaded Q and the noise temperature of AFR, respectively. To clarify the noise sources of the resonators, Fig. 3 is converted as follows.

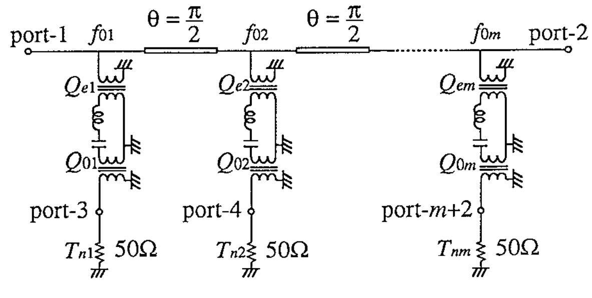

Fig. 4 Equivalent Conversion of BEF Circuit

In Fig. 4, we introduced m terminals connected to 50Ω resistances with temperature of T_{nl} (l=1, 2, ..., m). Noise powers proportional to the noise temperatures are entered in BEF circuit to generate noise power at the input and output terminals. Denoting the transmission S parameter of BEF by S_{21} and the S parameters from the noise sources to the output terminal by $S_{2,l+2}$, the total noise power generated at the output terminal is expressed by following equation:

$$N_{\text{out}} = |S_{21}|^2 N_{\text{in}} + \sum_{l=1}^{m} |S_{2,l+2}|^2 kT_{nl}B. \tag{6}$$

The input and output powers S_{in} and S_{out} are connected with the transmission S parameter:

$$S_{\text{out}} = |S_{21}|^2 S_{\text{in}}. \tag{7}$$

Using (6), (7) and the definition of NF, the NF value of a AFR BEF is expressed by

$$\begin{aligned} \text{NF} &\equiv 10\log\left(\frac{N_{\text{out}}/S_{\text{out}}}{N_{\text{in}}/S_{\text{in}}}\right) \\ &= 10\log\left(1 + \sum_{l=1}^{m}\frac{|S_{2,l+2}|^2 kT_{nl}B}{|S_{21}|^2 N_{\text{in}}}\right) \\ &= 10\log\left(1 + \sum_{l=1}^{m}\frac{|S_{2,l+2}|^2}{|S_{21}|^2}\frac{T_{nl}}{T_0}\right). \end{aligned} \tag{8}$$

In the last arrangement of the equation, the incident noise power is assumed to equal the white noise power:

$$N_{\text{in}} = N_0 = kT_0B. \tag{9}$$

As shown in the above procedures, the AFR filter can readily be designed by expressing the AFR as a passive resonator with the temperature T_n. Minimizing AFR noise temperature enables optimum noise design for AFR filters.

As an example, the following describes the noise analysis of a three-pole AFR BEF utilizing the Tchebysheff type filter[4]. The equivalent circuit of a three-pole BEF is obtained by substituting 3 into m in the Fig. 4. Table 1 shows the design values of a three-pole BEF for this experiment.

Table 1 Design Values of a Three-pole BEF

pole no.	resonance frequency (f_0)	unloaded Q (Q_0)	external Q (Q_e)
1	918.387MHz	44300	7390
2	918.494MHz	47100	4810
3	918.593MHz	56000	6600

The calculation formula is obtained by substituting 3 into m in (8). The numerical values of S_{21}, S_{23}, S_{24} and S_{25} required for the analysis are determined by utilizing a circuit simulator, as shown in Fig. 5.

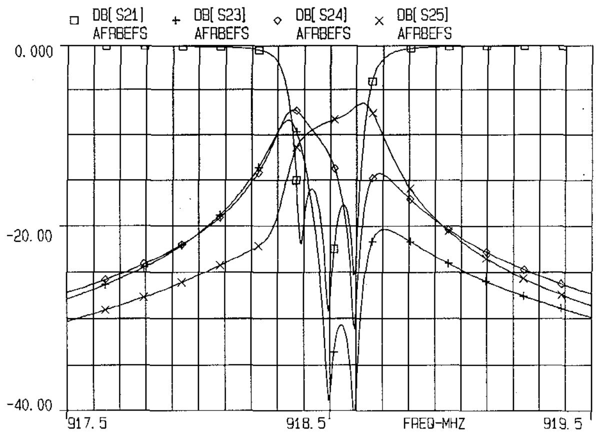

Fig. 5 S Parameters of the Three-pole BEF

The NF value of the three-pole AFR BEF can theoretically be calculated from the S parameters in Fig. 5 and the observed noise temperatures of AFR.

IV. Experimental Results

This section describes the comparison between the theoretical values and the observed results of a Tchebysheff-type three-pole AFR BEF designed in this paper. The minimum-noise design of AFR was performed according to the (4) and (5). The electrical length $\theta=\pi/2$ shown in Fig. 4 are determined around the center frequency of 918.5MHz.

The theoretical calculation requires the noise temperatures of AFRs. The following describes the noise measurement procedure and its results of a one-pole AFR BEF. Fig. 6 shows the noise temperature measurement system for one-pole AFR BEF. A TM110 mode dielectric resonator with unloaded Q of about 7500 and low-noise amplifier with NF of 2.6dB are used for this AFR[3]. At the both sides of the low-noise amplifier in active feedback loop, isolators are connected to match the input and output loads. The low-noise amplifier will amplify only the incident signal, so that the actual AFR circuit can be constructed in the same way as that of the analysis model.

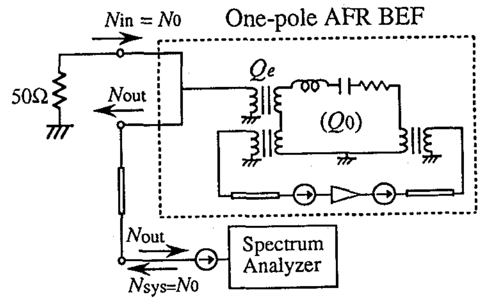

Fig. 6 Noise Temperature Measuring System

When N_{in} and N_{sys} are assumed to be the white noise power N_0, the formula for the noise temperature measurement is expressed by

$$T_n = T_0 + \frac{Q_e}{2Q_0}\left(1 + \frac{Q_0}{Q_e}\right)^2 \left(\frac{N_{out}'}{N_0'} \times 10^{\frac{NF_{sys}}{10}} - 1\right) T_0, \quad (10)$$

where N_{out}', N_0' denotes the noise power observed by a spectrum analyzer, and NF_{sys} the noise figure of the measuring instruments. Table 2 shows the observed noise temperatures of AFR calculated by (10).

Table 2 Observed Noise Temperature of AFR

T_{n1}	T_{n2}	T_{n3}
2680K	2740K	2760K

The theoretical NF value of the three-pole AFR BEF can be calculated by substituting the results shown in Table 2 and Fig. 5 into (8).

The following describes the NF measurement and its results of the three-pole AFR BEF. The diagram and external view of the NF measuring system are shown in Fig. 7.

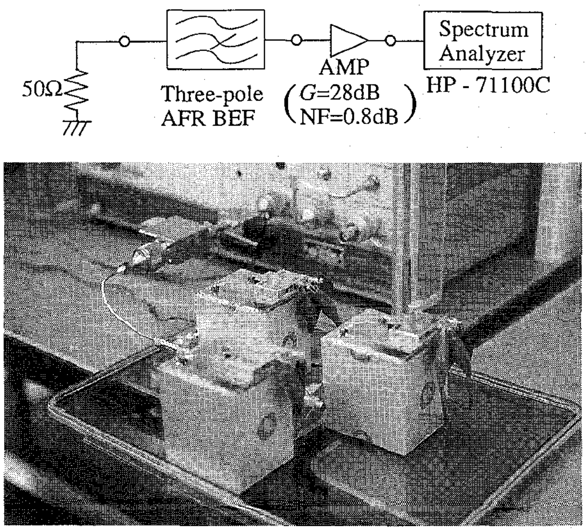

Fig. 7 NF Measuring System for three-pole AFR BEF

The NF measurement formula for AFR BEF is expressed as following equation.

$$NF = 10\log\left(\frac{1}{|S_{21}|^2}\cdot\frac{N_{out}'}{N_0'}\times 10^{-\frac{NFsys}{10}} - \frac{|S_{22}|^2}{|S_{21}|^2}\right) \qquad (11)$$

where N_{out}' denotes the output noise power of three-pole AFR BEF observed by a spectrum analyzer.

The observed results of insertion loss and return loss of the three-pole AFR BEF are shown in Fig. 8.

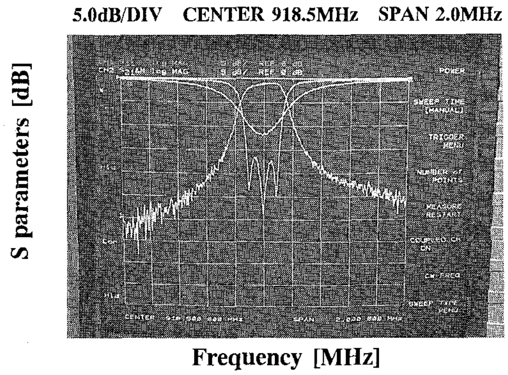

Fig. 8 Insertion Loss and Return Loss of the Three-pole AFR BEF

The insertion loss without active feedback loop is also shown in Fig. 8. The magnitude of the S parameters S_{21} and S_{22} shown in (11) are measured by using Fig. 8.

The noise output power of the three-pole AFR BEF is shown in Fig. 9.

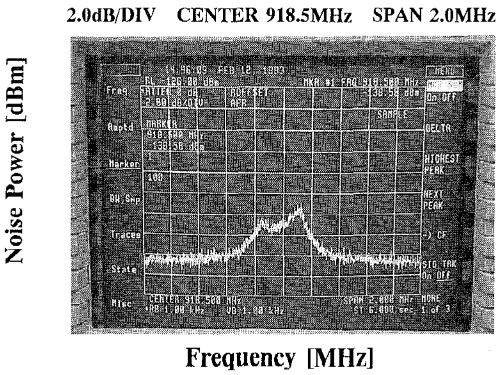

Fig. 9 Noise Output of the Three-pole AFR BEF

The output noise power N_{out}' shown in (11) is measured by using the result of Fig. 9.

Fig. 10 shows the observed NF value obtained by (11) and the theoretical NF value calculated from the noise temperatures in Table 2.

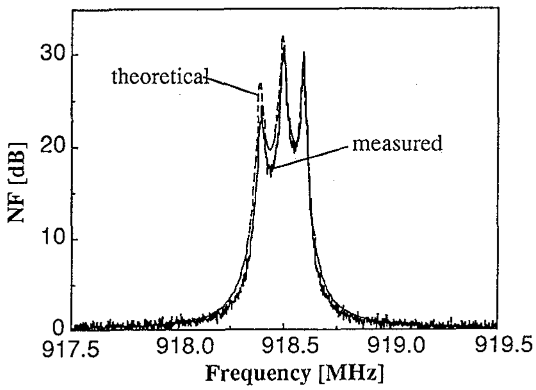

Fig. 10 Observed and Theoretical NF Values of Three-pole AFR BEF

It is found that the observed values are in good agreement with the theoretical value within the allowable error of noise amplitude.

V. Conclusions

In a filter design system which introduces noise temperature into the AFR, AFR BEF can be designed using techniques for the conventional passive BEF.

In this system, the passive BEF circuit used for electrical design is also useful for the noise analysis of the AFR BEF.

This analysis revealed that the NF value of the AFR BEF is calculated from the noise temperatures of AFRs. The optimum NF value is obtained by minimizing these noise temperatures.

The noise design of three-pole AFR BEF has been discussed in this study. It was found that the observed NF of the three-pole AFR BEF agree well with the theoretical values deduced from the designed S parameters and the observed noise temperatures of AFRs.

References

[1] T. Hirota and T. Itoh, "Recent Progress in Filters for Mobile Communications," *URSI ISSSE Symp. Dig.*, pp. 856-858, Sep. 1992.

[2] H. Matsumura and Y. Konishi, "An Active Microwave Filter with Dielectric Resonator," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 323-325, 1979.

[3] Y. Ishikawa, S. Yamashita and S. Hidaka "Noise Temperature of Active Feedback Resonator (AFR)," *Technical Report of IEICE Japan*, MW92-102, pp. 39-46, 1993.

[4] G. L. Matthaei, L. Young and E. M. T. Jones, "Microwave Filters, Impedance-Matching Networks, and Coupling Structures," McGraw-Hill Book Company, pp. 725-773, 1964.