Temperature Compensation of Resonators Using Different Materials and Suitable Dimensions

Johannes Müller, Michael Höft

Communications Laboratory of European Technology Center (www.panasonic-eutc.com),
Panasonic Electronic Devices Europe GmbH, Zeppelinstr. 19, D-21337 Lueneburg, Germany,
Phone: +49 (0) 4131 899-228, fax: +49 (0) 4131 899-262, email: Michael.Hoeft@eu.panasonic.com

Abstract — The mode-matching method is applied to synthesize stepped combline resonators with a perfectly compensated temperature characteristic. Besides a convenient choice of materials, emphasize is put on the correct choice of the dimensions, to obtain a trade-off with the resonators quality factor. Several resonators have been fabricated to verify the accuracy of the method. A 2.14 GHz, 9-pol filter was designed and measured. The temperature drift was improved from -47 kHz/K to 1 kHz/K.

I. Introduction

Combline resonators are widely used in communication systems due to their compact size, relatively high Q, comfortable tunability and low cost, compared to dielectric resonators. The drift of resonance frequency over temperature is an inconvenience because it limits the overall characteristic of the system in which the resonator is a part of. A simple method to decrease the frequency drift is to use materials with a low coefficient of thermal expansion (CTE), such as INVAR. This material however is heavy and difficult to manufacture. Craven published first the use of different materials [1], but it was more an experimental way to solve this problem. The first theoretical work on temperature compensation was accomplished by Wang in [2]. The structure was a reentrant combline resonator and mode matching analysis was done parallel to the z-direction. Further, the temperature drift was calculated via perturbation theory. In this paper, the classical mode-matching method is used to analyze the combline resonators as depicted in Fig. 1. The matching planes are perpendicular to the z-direction. The calculated resonant frequencies were compared to results obtained with Ansoft HFSS and CST Microwave Studio and found to be accurate within 0.1%. The influence of the resonators structure on the temperature behavior was object of our investigation. Varying the dimension of the resonator can improve the temperature behavior significantly. A complete 9-pol filter was designed using compensated resonators. The measured results show excellent temperature behavior.

II. Analysis of the Structure

The analyzed structure is illustrated in Fig. 1. All parts are assumed to be perfectly conducting, cylindrical in shape and have a circular cross section.

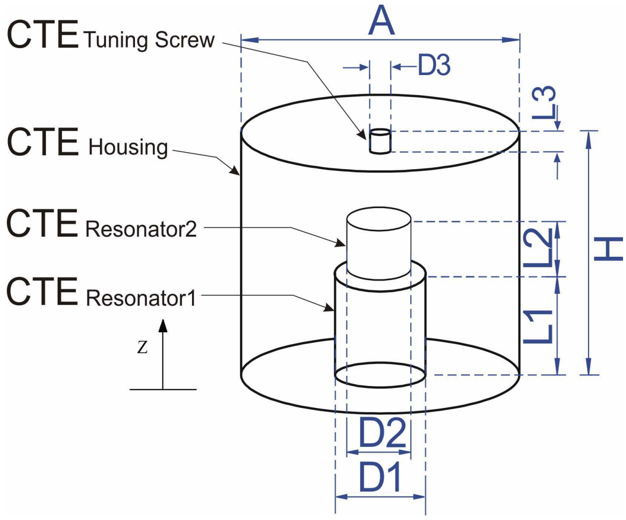

Fig. 1 Structure of the stepped combline resonator

Two different structures can be distinguished: The simple combline resonator with a straight resonator rod and thus $D1 = D2$, and the stepped combline resonator (SCR) with two sections of arbitrary length and $D1 \neq D2$. A tuning screw, simulated as a conducting cylindrical rod, concentrically placed under the top of the housing can be included into the calculation. All dimensions vary with temperature due to the CTE of their materials. The resonant frequency of the structure is calculated via the classical mode-matching method. The electromagnetic field of each waveguide section can be expanded into a modal series. The continuity condition states, that the tangential electric and tangential magnetic fields on both sides of each discontinuity have to be equal. Furthermore the tangential electric field on the conductor vanishes. The eigenmodes of the two waveguides couple with each other in such a way, that the continuity condition is satisfied. The coupling coefficients are calculated by integrating the products of the two eigenmode field vectors over the common cross section. A general formulation of the described discontinuity problem has recently been given by Orfanidis in [3]. It should be mentioned that due to the rotational symmetry of the junctions, only axially symmetric TM_{oj} modes can be excited in the cylindrical and coaxial waveguide and need to be considered besides the propagating TEM mode. The general scattering Matrix (GSM) is the most common way to solve cascaded discontinuity problems.

For the coaxial step it should carefully be distinguished between a boundary enlargement- and reduction type [6]. The integration should always be taken over the larger cross-section, which leads to different formulations for the two cases:

- Boundary enlargement type ($D_a > D_b$)

$$
\begin{aligned}
&[S_{11}] = \left([E_a]+[R][C]^T\right)^{-1}\left([E_a]-[R][C]^T\right),\\
&[S_{21}] = 2\cdot\left([C]^T[R]+[E_b]\right)^{-1}[C]^T,\\
&[S_{12}] = 2\cdot\left([E_a]+[R][C]^T\right)^{-1}[R],\\
&[S_{22}] = \left([C]^T[R]+[E_b]\right)^{-1}\left([C]^T[R]-[E_b]\right),\\
&\text{with } [R]=[Z_a][C][Y_b].
\end{aligned} \tag{1}
$$

- Boundary reduction type ($D_a < D_b$)

$$
\begin{aligned}
&[S_{11}] = \left([C][R]+[E]_a\right)^{-1}\left([C][R]-[E]_a\right)\\
&[S_{21}] = 2\cdot\left([E]_b+[R][C]\right)^{-1}[R],\\
&[S_{12}] = 2\cdot\left([C][R]+[E]_a\right)^{-1}[C],\\
&[S_{22}] = \left([E_b]+[R][C]\right)^{-1}\left([E]_b-[R][C]\right),\\
&\text{with } [R]=[Z]_b[C]^T[Y]_a,
\end{aligned} \tag{2}
$$

where $[Y]=diag(Y_i)$ is the diagonal matrix of the modal wave admittances, $[Z]=[Y]^{-1}$ corresponds to the wave impedances, $[E]$ is the identity matrix and $[C]$ is the coupling matrix containing the coupling coefficients:

$$
c_{mn} = \int_S \boldsymbol{e}_m^{(a)}\boldsymbol{e}_n^{(b)}dS, \quad m,n=1,2,\ldots\infty\,. \tag{3}
$$

The subscript a and b denote the left and right side of the junction respectively. It can easily be shown, that the two formulations (1) and (2) can be deduced from each other. An analytic expression can easily be found for (3) leading to a fast computation of the coupling matrix. The overall scattering matrix can be obtained by cascading the GSMs of all discontinuities and transmission line sections [4]. Introducing the short-circuit at the bottom and top of the resonator leads to an overall equation system. The roots of the determinant of this system are the resonant frequencies. Accurate results can be achieved when the number of modes in the circular waveguide is above 20. The optimum number of modes in the coaxial waveguide sections depends on the diameter and is given by:

$$
\frac{M}{N} = \frac{A-D}{A_W}\,, \tag{4}
$$

with N and M being the number of modes in the circular and coaxial waveguide respectively, A and D are the outer and inner diameter of the coaxial-waveguide and A_W is the diameter of the circular waveguide. This mode-ratio is chosen to avoid the convergence phenomenon [6] and leads to very accurate results even for a modest number of modes taken into account. This is due to the fact that the two errors that take place while truncating the number of modes cancel out each other [7].

III. TEMPERATURE COMPENSATION

The temperature characteristic of a resonator made out of one material depends on the CTE of the material as well as the resonant frequency [4]:

$$
f(\Delta T) = f_0 \frac{1}{(1+CTE\cdot\Delta T)}\,. \tag{5}
$$

A 2 GHz resonator made out of aluminum undergoes a shift in resonant frequency of -47.6 kHz/K, which corresponds to -23.8 ppm.

A. Compensation with a simple combline resonator

The frequency drift is mostly due to the change of resonator length L and height H, and thus the change of the capacitive gap. For a given height and resonant frequency, this gap depends however on the outer and inner diameter as well. A first approach to compensate the frequency drift is to use a straight rod made out of a material with a lower CTE, such as iron or brass. It can be shown, that the temperature behavior depends strongly on the resonators dimensions, such as A, H, D, and L. In Fig. 2 the temperature behavior is shown as a function of the inner and outer diameter. In order to analyze the temperature behavior at a constant resonant frequency, the length L, and thus the capacitive gap, is adjusted for each [A,D]-parameter set. The straight dashed line in Fig. 2 marks the optimum diameter ratio of $A/D=3.6$ which leads to a maximum Q-factor. The dash-dotted contour lines display the depth of the capacitive gap.

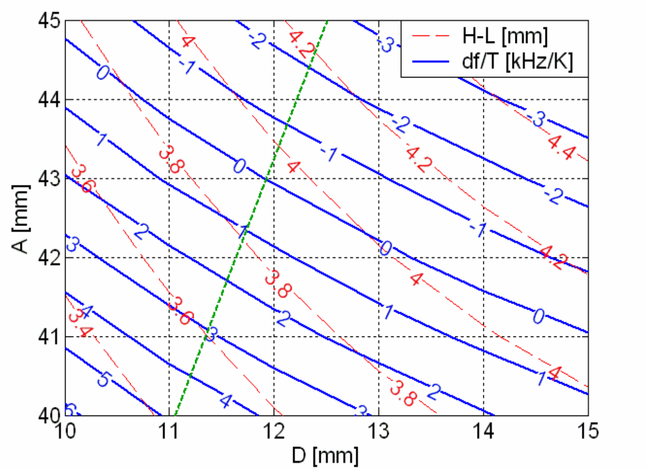

Fig. 2 Parameter-sweep for a combline resonator with aluminum housing, iron rod, H = 28 mm, fo= 2.017 GHz

The optimum Q-factor while achieving temperature compensation would be for an outer diameter of 43 mm. Alternatively, the height H can also be used as a sweep parameter. Depending on the specification for the overall system (e.g. Filter panel) the outer dimensions of the resonator might have a fixed value and only the inner diameter could be varied. This restriction might lead to an inconvenient A/D ratio and thus a lower Q-factor when aiming for a temperature compensated resonator. The first approach to overcome this problem is to use two different materials for the resonator rod. While making the upper part out of a material with a lower CTE, the lower section should be out of the same material as the housing in order to achieve a Q-factor improvement by introducing a base rounding [8]. However, the compensation could only be achieved, if the resonator would have a positive frequency drift for the case that the coaxial rod was made completely out of the material with the lower CTE. The second approach is to use a stepped combline resonator and additional degrees of freedom. It should be noted, that the stepped combline resonator with a larger second section should also be considered when the overall height of the resonator has to be kept very small [9].

B. Compensation with a stepped combline resonator

When introducing a step in the resonators rod, the gap depends further on the diameter and length of the new section. The temperature compensation can thus be controlled more easily using these additional two degrees of freedom [10]. A possible third degree of freedom could be using a different material for this new section. Another resonator with the same resonant frequency and height H as in the previous case is studied with a fixed outer diameter of 40 mm. A parameter sweep is made over the diameter and length of the additional section, as illustrated in Fig. 3. Temperature compensation can be achieved with D2 = 12.25 mm. Further, a resonator was designed for a resonant frequency of 1.95 GHz. The sweep has been calculated with L2 and D2 as parameters. For optimum Q-factor D1 = 11.1 mm was chosen.

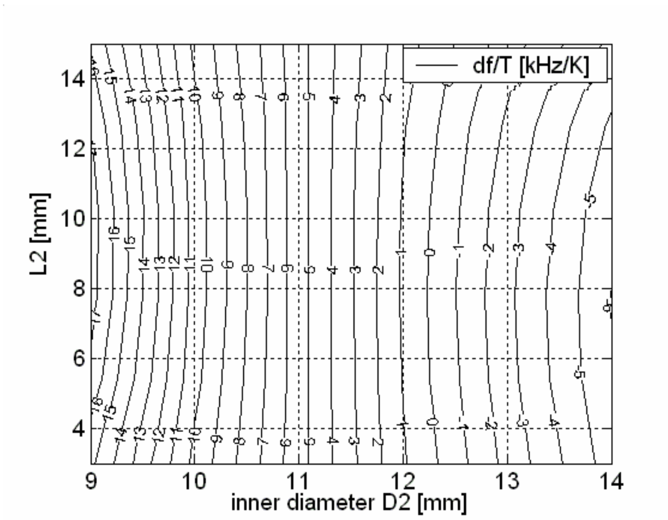

Fig. 3 Parameter-sweep for a SCR with aluminium housing, iron rod, H=28 mm, A=40 mm, D1=11.1 mm, fo =2.017 GHz

Alternatively, the sweep could be made over D1 and L1, but it is preferable to choose the lower section with the optimum diameter, because the electrical current is larger near the bottom and an inconvenient diameter ratio would thus increase the losses.

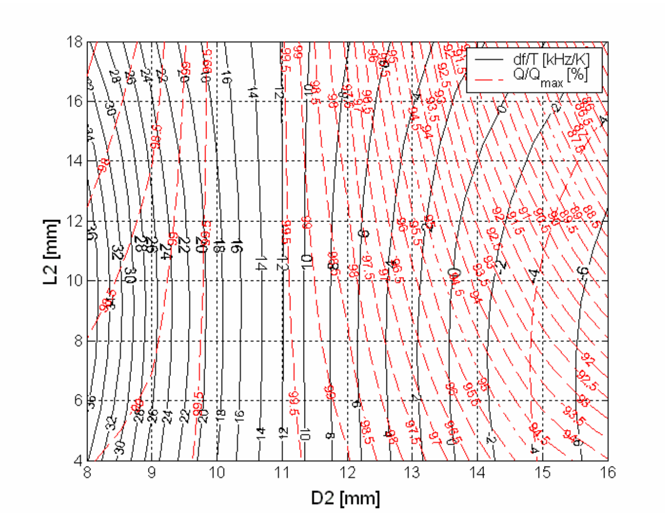

Fig. 4 Temperature behaviour versus Q-factor degradation of SCR with D1 = 11.1 mm, H = 28mm, A = 40 mm.

As shown in Fig. 4 the resonator can be temperature compensated for D2 = 13.6 mm. For the same parameter sweep a Q-factor calculation has been made with a finite element analysis, taking into account the surface losses. To overcome numerical uncertainties of the Q-factor calculation, polynomial curve fitting is applied [8]. The resulting values are plotted into the same graph for easy evaluation of a trade-off between temperature compensation and Q-factor degradation. A compensated combline filter can be designed with a larger bandwidth compared to an uncompensated filter. This leads to an insertion loss improvement that outweighs the eventual decrease of the Q-factor. D2 = 13.5 mm and L2 = 4 mm should be chosen for temperature compensation and minimum Q-factor degradation to 97% of the maximum value. A 2.14 GHz, 9-pol filter, as shown in Fig. 6, was designed and measured. The measurement is depicted in Fig. 5. In the temperature range from -10°C to 70 °C, the -20dB band stop edges undergo a frequency shift of -1 kHz/K which corresponds to an improvement of 47 kHz/K.

VI. Conclusion

The temperature behavior of straight and stepped combline resonators was analyzed using the mode matching method. It was shown that temperature compensation can be achieved for various structures, depending on the proper choice of materials and dimensions. It has further been shown, that for some cases the stepped combline resonator has advantages over the straight resonator. Measurements for a compensated 9-pol filter have been presented.

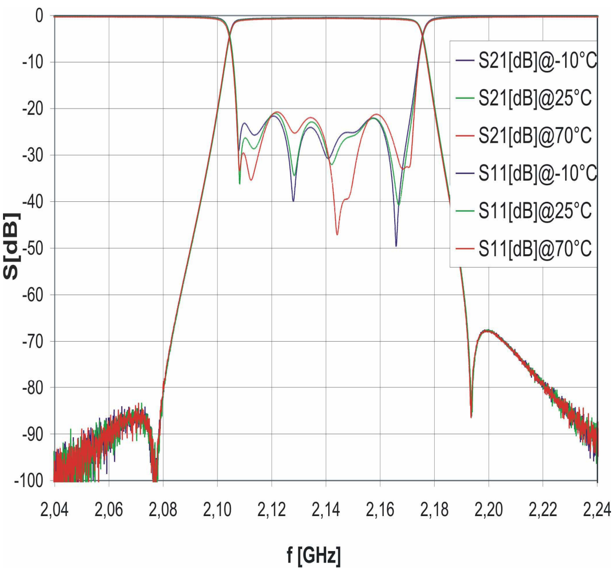

Fig. 5 Measurement of the 9-pol TX Filter with temperature compensated stepped combline resonators.

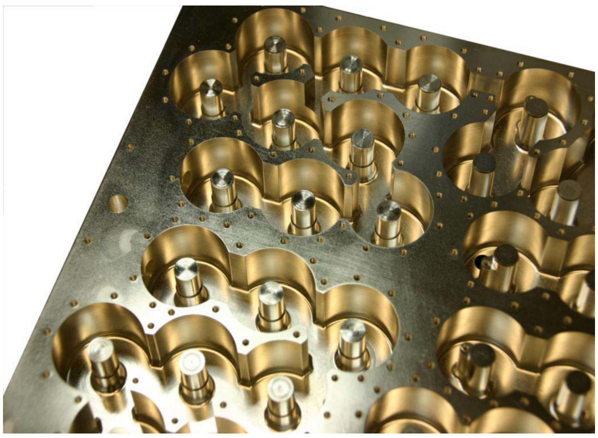

Fig. 6 TX Filter with temperature compensated stepped combline resonators.

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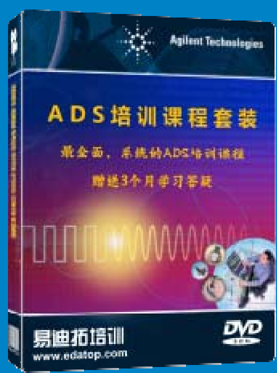

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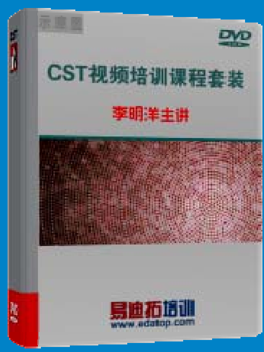

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