Passive electromagnetic compensation of permittivity changes in microwave circuits

Jan Hesselbarth and Rüdiger Vahldieck

Laboratory for Electromagnetic Fields and Microwave Electronics
Swiss Federal Institute of Technology (ETH), Gloriastrasse 35, 8092 Zürich, Switzerland

***Abstract* — Microwave circuit elements are proposed which are inherently independent of small variations of the material permittivity. Different structures are investigated which can be used to obtain a temperature-independent resonance frequency, group velocity, or phase shift, respectively, although the permittivity of the involved materials varies.**

I. INTRODUCTION

Microwave systems are often required to work properly over a large temperature range. On the system level, this is usually achieved by appropriate calibration. Active components, like amplifiers, can be temperature–compensated by an appropriate feedback loop. Passive components can be made of temperature-compensated materials (e.g. Invar waveguides or dielectric resonators based on compensated titanates like $BaTiO_4$). These materials, however, are economically, electrically and mechanically unfavorable. Therefore, a long track of publications exists proposing temperature–independent circuits either by using materials having temperature variations of their respective permittivities of the opposite sign [1]-[2] or by compensating the change of permittivity using the thermal expansion of the circuit [3]-[4].

In this paper, it will be shown that simple circuits can be designed in a way, so that small permittivity variations have no or negligible effect on the electrical performance. Properties like resonance frequency, group velocity, or phase shift can be made independent of permittivity variations of the involved materials. The compensation effects shown below are due to the particular circuit topology, working as a standalone measure for temperature compensation. They can, however, be combined with the traditional methods of compensation mentioned before.

The first structure is a series connection of a transmission line and a (lumped) capacitor. This circuit was used for the design of compact low-pass filters [5]. A closer look reveals that the fundamental resonance of this circuit is independent (to a first degree) of the substrate's permittivity of the involved transmission line. The second order effects can be compensated with a small temperature dependence of the capacitor. This circuit can be used as temperature-compensated resonator.

The second structure is a dielectric waveguide carrying a mode which has a cutoff frequency. At some frequency, the derivative of the group velocity with respect to the dielectric permittivity is zero. This opens the possibility to use, e.g. rutile-based dielectric waveguides as delay lines.

The third structure is the stepped impedance resonator. Herein, compensation is achieved by two dielectric materials having temperature coefficients of opposite sign [2]. However, these temperature coefficients may differ largely in magnitude, as the example will show.

The fourth structure is obtained by periodically cascading the third structure: it is a transmission line composed with periodically varying impedances. The variation of the permittivities does not only affect the electrical lengths of the line sections, but also their impedances and thus the impedance ratio. The larger the ratio of high to low impedance is, the longer the electrical length of the entire line is. The variation of electrical length of a single line section can be partly compensated by the variation of the impedance ratio.

Although the use of uncompensated, low-cost, and low-loss dielectrics is tempting, the applications for the first, third and fourth proposed structures are limited by the low *Q*-factor caused by conductor loss.

II. SEMI–LUMPED RESONATOR CIRCUIT

Figs. 1a,b show cascaded structures of a lumped capacitor and transmission lines (impedance Z_L, electrical length Q_L) [5]. The resonance frequency w_0 is obtained from cascaded ABCD matrices and given by

$$\tan \Theta_L = \frac{1}{2 w_0 C Z_L} \tag{1}$$

For short lines, where $\tan \Theta_L = \Theta_L$, the resonance frequency becomes independent of the line permittivity. Note that the compensation effect occurs only for the first resonance where the transmission line is short (i.e. $Q_L < p / 2$). In order to keep the line short, the capacitance C and the line impedance Z_L must be large. The losses of the high impedance transmission line are the primary limitation of the resonator *Q*.

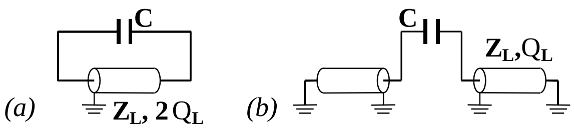


Fig. 1: *Semi-lumped resonator circuits.*

As the line is of course longer than zero, the remaining variation can be compensated by an appropriate variation of the capacitance. Consider the following linearized definition of the thermal variation of permittivity

$$e_{rel}(T_0 + \Delta T) = e_{rel}(T_0) \cdot (1 + a\,\Delta T) \qquad (2)$$

The coefficients of the thermal variation of the respective permittivities of the capacitor and the transmission line are a_{CAP} and a_{LINE}. Hereby, a_{LINE} affects both Z_L and Q_L of the line. The value of the thermal variation of the capacitance required for complete compensation can be found by inserting (2) into (1), which yields

$$\frac{\sin(2\Theta_L(T_0))}{2\Theta_L(T_0)} = \frac{1}{1 - \dfrac{2a_{CAP}}{a_{LINE}}} \qquad (3)$$

This formula assumes TEM lines. However, for non-TEM lines, effective coefficients can be derived. Since thermal expansion effects are usually small compared to permittivity variations, variations of the resonance frequency which are due to thermal expansion can be accounted for by the same method of compensation.

For a given length Q_L, equation (3) defines the ratio of a_{CAP} and a_{LINE} being necessary for complete compensation. As shown in Fig. 2, a_{CAP} can be much smaller in magnitude than a_{LINE} because it has to compensate second order effects only.

Two application examples will be briefly described. Consider first a MMIC resonator circuit (Fig. 3). A MIM capacitor made from Si_3N_4 has almost temperature-stable capacitance as the increase of permittivity and the thermal expansion of the ceramic cancel each other [6]. The microstrip line is composed of a *5mm* wide, *4mm* thick gold strip on *3.8mm* thick BCB dielectric and gold ground. These materials (BCB/Benzocyclobutene, e_{rel} = *2.65*, *tand* = *0.0018* at *10 GHz*, thermal expansion *+50ppm/K*, permittivity variation *–160ppm/K* [7], s_{Au} = *45 MS/m*) give an impedance *Z = 67W* (*+80ppm/K*), an effective permittivity of *2.275* (*–140ppm/K*), and a thermal variation of the electrical length of *–70 ppm/K*. The loop circuit (Fig. 1a) formed by *C = 2.36pF* and *480mm* transmission line shows a resonance frequency (as obtained by circuit simulation) of *10.0 GHz* with a thermal variation of only *–6 ppm/K*, which is an order of magnitude better than the variation of the electrical line length. The entire circuit with *50W* lines connected was simulated using a 3D field solver (HFSS). While assuming perfectly conducting metal, a bandstop characteristic was obtained. The resonance frequency of *9420 MHz* had a variation of *–10.7ppm/K*. If finite conductivity was assumed, however, the circuit simulation resulted in an unloaded *Q = 14*, whereas HFSS did not give any filter response. This example shows the incomplete first order compensation, reducing the temperature shift by about one order of magnitude. Secondly, it shows that conductor loss in the high-impedance transmission line may become prohibitive.

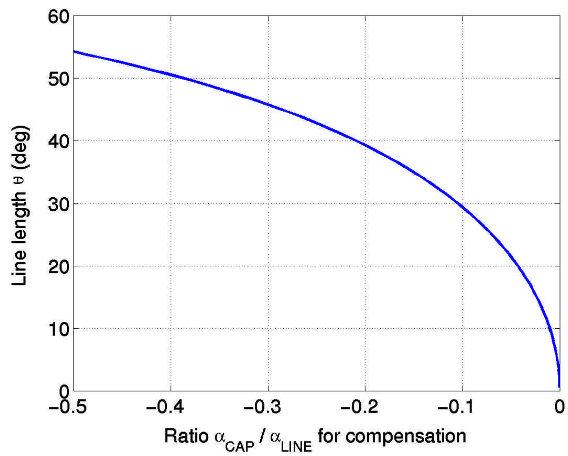


Fig. 2: *Plot of equation (3) showing* a_{CAP} *necessary for complete compensation.*

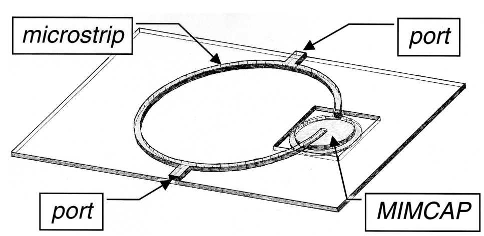
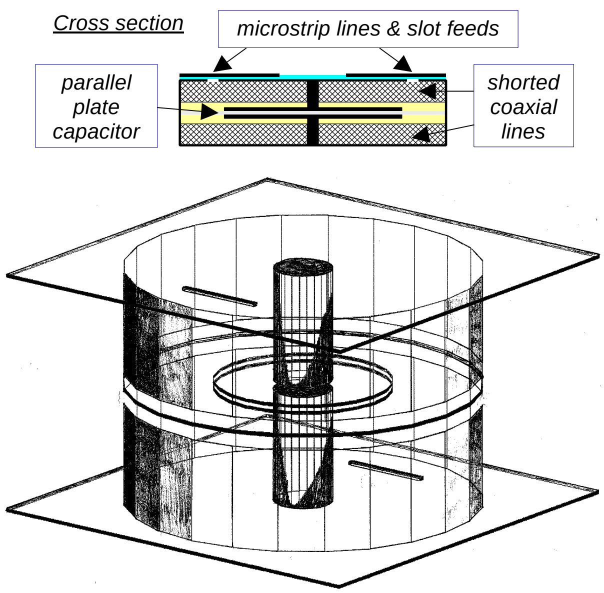


Fig. 3: *Drawing of a bandstop filter based on the microstrip-MIMCAP loop resonator circuit (as in Fig. 1a).*

The second example is a coaxial resonator (Fig. 4). It is represented by the chain circuit (Fig. 1b). The coaxial lines are based on rutile (TiO_2, e_{rel} = *100 / –900ppm/K*, *tand* = *0.0002*) and the parallel plate capacitor uses alumina (Al_2O_3, e_{rel} = *10.0 / +100ppm/K*, *tand* = *0.0001* [8]). A spacer (e_{rel} = *2.2*) separates lines and capacitor, and thick film silver metal (*s = 55 MS/m*) is assumed. The resonator is fed by slots coupled to microstrip lines.

Complete compensation using the chosen materials requires a line length (see (3)) of Q_L » *31°*. With

e_{rel} = *91...100* at *736 MHz*, this corresponds to a geometrical length of *3.5...3.7mm*. This value neglects the effects of the spacer section and the fringing fields. In fact, the example resonator uses a line length of *3.5mm*. From (1) and taking Z_L = *11W*, it follows *C = 16pF*. This value is much larger than the actually implemented capacitor of *6.3pF*, apparently because the series capacitance is enhanced as the coaxial line ends may couple directly. Field simulations (HFSS) resulted in a resonance frequency of *736±1 MHz, 0...+2ppm/K* and *Q = 670±40* (more accurate results using HFSS seem to be both difficult and questionable). The complete compensation is clearly shown. Thermal expansions are not yet taken into account, but they are small and could also be compensated.



coax diameter: 12mm/2mm | impedance: 11±0.25Ω
overall thickness: 8mm | capacitance: 6.3pF
line lengths: 2 × 3.5mm | resonance: 736MHz

Fig. 4: *Temperature-compensated resonator. Coaxial line based on rutile and capacitor made from alumina.*

The Q-factor is determined by both dielectric and conductor loss. An optimally chosen coaxial line would have about *9%* less losses. Pure rutile can have only *10%* of the dielectric loss of compensated titanates of high permittivity. Therefore, the proposed resonator is expected to have a higher Q-factor than conventional high-permittivity quarterwave coaxial resonators.

III. COMPENSATED DELAY ELEMENT

The group delay in a dispersive transmission line is frequency-dependent. The dispersion relation of a cylindrical waveguide filled with a material of relative permittivity e_{rel} is known as $e_{rel} k_0^2 = b^2 + k_c^2$, where k_0, b, k_c are the wave numbers, respectively, in free space, in propagation direction, and in transverse direction. At the frequency f_{vgr0}, the derivative of the group velocity with respect to the permittivity is zero,

$$\frac{\partial v_{group}}{\partial e_{rel}} = 0 \qquad \rightarrow \qquad \frac{f_{vgr0}}{f_c} = \sqrt{2} \tag{4}$$

wherein f_c denotes the cutoff frequency. This relation holds for all modes (except TEM mode) in homogeneous cylindrical waveguides. Fig. 5 illustrates the cancellation effect. The group velocity is shown to be almost independent of permittivity variations for both rectangular waveguide and NRD guide [9] (unlike with TEM line).

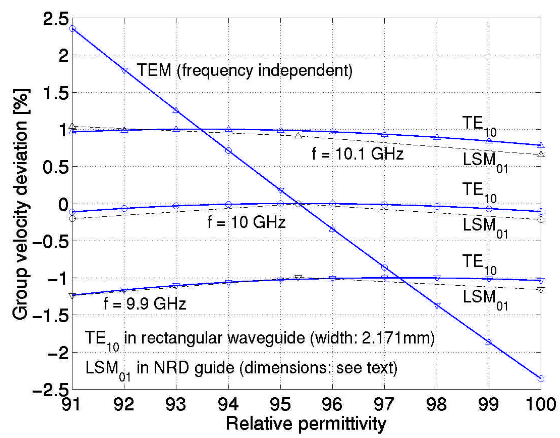


Fig. 5: *Group velocity deviation as a function of permittivity.*

The group delay compensation was applied to the NRD guide, which has low loss at high frequencies. The NRD guide shown in Fig. 6 has a permittivity independent group velocity of *22.5mm/ns* at *10 GHz*. Assuming loss tangents of *0.001* (rutile), *0.0007* (alumina), and *s = 45 MS/m*, the straight guide has losses of only *0.32dB/ns* at *10 GHz*. The frequency where compensation occurs is close to the transmission loss minimum of the NRD guide.

IV. STEPPED IMPEDANCE RESONATOR

A stepped impedance resonator (Fig. 7) has been proposed in [2] for temperature-compensation of dielectric materials. Again, the structure is independent to a first degree of the permittivity of the shorted transmission line, and second order effects are compensated by an appropriate, small permittivity variation of the material of the open transmission line. A stepped impedance resonator antenna, based on rutile and alumina, has been reported in [10].

V. STEPPED IMPEDANCE TRANSMISSION LINE

In a transmission line being composed of short line sections of periodically varying impedances, the overall electrical length is affected by both the impedances and the permittivities. The larger the ratio of high to low impedance (impedance ratio) is, the longer the overall electrical length is (slowing effect). Compensation is achieved if the line sections are designed such that a decrease of permittivity (i.e. reduction of electrical length) causes an increase of the impedance ratio (i.e. larger slowing effect). It is necessary that the low impedance sections are made using a rather stable dielectric, whereas the high impedance sections involve the more temperature-variable dielectric.

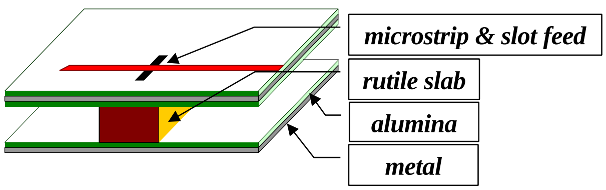


Fig. 6: *NRD guide: a rutile slab (2.3mm x 2.2mm) sandwiched between alumina plates (0.254mm thick).*

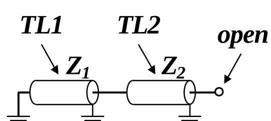


Fig.7: Principle of a stepped-impedance resonator.

Consider the following idealized example. The low impedance sections (impedance Z_{low}, electrical length E_{low}) are made from alumina based TEM lines, and the high impedance sections (Z_{high}, E_{high}) are based on rutile. A variation of temperature will change Z_{high} (*+450ppm/K*), E_{high} (*–450ppm/K*), Z_{low} (*–50ppm/K*), and E_{low} (*+50ppm/K*). Therefore, the impedance ratio changes by *+500ppm/K*, and the average electrical length changes by *–200ppm/K*. If all sections have an electrical length of *l/50* and $Z_{high}/Z_{low}=9.5$, the variation of *+500ppm/K* in impedance ratio results in a slowing factor of *1.65* with a variation of *+200ppm/K* (Fig. 8). Thus a stabilized effective wave velocity of *27.6mm/ns* is obtained.

VI. CONCLUSION

In this paper, it was shown that microwave circuits can be designed in a way such that small variations of material permittivity have no or negligible effect on the electrical performance. This opens the possibility to use low-cost, uncompensated materials in microwave circuits. Several structures for the compensation of the resonance frequency, the group velocity, and the phase shift, respectively, were presented. The proposed new methods of compensation are based on circuit topology only and can be used in conjunction with traditional methods of compensation.

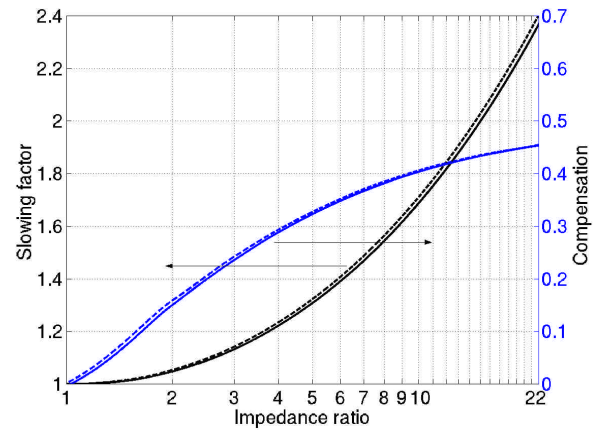


Fig. 8. *Left: Velocity slowing factor as a function of the impedance ratio of a periodically stepped impedance line. Right: Ratio of relative variation of slowing factor to relative variation of impedance ratio. Sections l/50 (solid) or l/90 (dashed) long.*

REFERENCES

[1] M.E. Tobar, J. Krupka, J.G. Hartnett, E.N. Ivanov, R.A. Woode, „High-Q sapphire-rutile frequency-temperature compensated microwave dielectric resonators," *IEEE Trans. UFFC*, vol. 45 (1998), no. 3, 830-836.

[2] S.-K. Lim, H.-Y. Lee, J.-C. Kim, C. An, "The design of a temperature-stable stepped-impedance resonator using composite ceramic materials," *IEEE Microw. Guided Wave Lett.*, vol. 9 (1999), no. 4, 143-144.

[3] M.R. Stiglitz, „Frequency tuning of rutile resonators," *Proc. IEEE*, 1966, 413-414.

[4] S.-W. Chen, K.A. Zaki, R.G. West, „A tunable, temperature compensated hybrid mode dielectric resonators," *IEEE MTT-S Digest*, 1989, 1227-1230.

[5] J.-W. Sheen, „A compact semi-lumped low-pass filter for harmonics and spurious suppression," *IEEE Microw. Guided Wave Lett.*, vol. 10 (2000), no. 3, 92-93.

[6] H. Ohno, Y. Katano, „Electrical properties of Silicon Nitride," *Materials Sci. Forum*, vol. 47 (1989), 215-227.

[7] D. Burdeaux, P. Townsend, J. Carr, „Benzocyclobutene (BCB) dielectrics for the fabrication of high density, thin film multichip modules," *J. Electronic Materials*, vol. 19 (1990), no. 12, 1357-1366.

[8] J. Krupka, K. Derzakowski, B. Riddle, J. Baker-Jarvis, „A dielectric resonator for measurements of complex permittivity of low loss dielectric materials as a function of temperature," *Meas. Sci. Technol.*, vol. 9 (1998), 1751-1756.

[9] T. Yoneyama, S. Nishida, „Nonradiative dielectric waveguide for millimeter-wave integrated circuits," *IEEE Trans. MTT*, vol. 29 (1981), 1188-1192.

[10] J. Hesselbarth, R. Vahldieck, "Compensation of temperature-induced changes of permittivity in antennas," *URSI Int. Symp. Electromagn. Theory*, Victoria, May 2001.