Ku-Band 3D LTCC Filter and BST-Varactor based Temperature Compensated Resonator

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***Abstract*—In this paper, a two-pole cavity resonator filter intended for UAV data-link at Ku-band is demonstrated. The design of the filter realised with LTCC integrated cavity resonators is described and validated by good agreement between specifications and measurements. The unloaded Q-factor of the proposed substrate integrated cavity resonator is assessed and the influence of the different lossy mechanisms present in the resonator is discussed. Finally, the RF-behaviour of a weakly-coupled doubly-terminated cavity resonator is investigated over temperature. A solution implementing a ferroelectric varactor coupled to the cavity resonator is assessed for the compensation of the shift of the resonance frequency observed for the substrate integrated resonator. The unloaded Q-factor of the temperature compensated resonator is measured and compared to the one of the un-compensated cavity.**

Keywords—cavity resonator filters, ceramics, thermal factors, ferroelectric capacitors.

I. INTRODUCTION

LTCC (Low-Temperature Co-fired Ceramics) technology has been used for years as size saver in frequency domains below 2GHz and several highly integrated consumer-oriented applications have demonstrated the advantages of ceramics [1], [2]. As the high frequency behaviour of ceramic tapes is being optimised by manufacturers and thanks to the constantly improved fabrication processes used to patterned structures, the application field of LTCC is moving towards higher frequency domains and it is now considered as one of the most promising technology in the Ku- and Ka-bands [3].

For applications operating in the low millimetre-wave range such as satellite communications and military data-link, this advent of LTCC at higher frequencies opens unprecedent opportunities. The use of LTCC makes possible realisation of 3D highly integrated multi-layer modules, in which the components are integrated monolithically. These fully integrated modules are smaller than standard hybrid integrated sub-systems made out of low-loss substrates like Teflon. They are more reliable, assume better performance and have more economic fabrication costs than conventional millimetre-wave modules.

This paper demonstrates a two-pole cavity resonator filter integrated in LTCC and designed for UAV (Unmanned Air Vehicle) data-link at Ku-band. The work presented here constitutes the first iteration of a longer development aiming at the realisation of a more elaborated filter foreseen for integration on both sides of the data-link: on-board in the UAV and in the base-station on ground.

TABLE I. SPECIFICATIONS OF THE KU-BAND FILTER

Parameter	Value
Centre Frequency F_0	15 GHz
-3 dB Bandwidth ΔF	800MHz
Insertion Loss in 200MHz *IL*	<0.5 dB
Reflexion S_{11}	<-16 dB
Out-of-Band Rejection at 12.6GHz	<-24 dB

The specifications of the filter are listed in Table 1. The out-of-band rejection specified at 12.6GHz aims at reducing the second harmonic generated by the local oscillator of the transceiver.

The sections II and III of the paper describe the design, the realisation and the characterisation of a single cavity resonator and a two-pole filter, both integrated in LTCC. The last section, section IV, focuses on the behaviour of the substrate integrated cavity resonator over temperature. It investigates the shift of the resonance frequency of the resonator over temperature and proposes a solution using ferroelectric varactor to compensate for the measured frequency shift.

II. DOUBLY TERMINATED SUBSTRATE INTEGRATED CAVITY RESONATOR

The cavity resonator is realised in 6-layer LTCC DuPont 943 substrate (ε_r=7.5) according to the Substrate Integrated Waveguide (SIW) technique. The side-walls of the cavity are implemented using rows of vias manufactured in LTCC and connecting two metal planes closing the cavity on the top and bottom sides. The pitch between two consecutive vias is 513µm (ca. 1/14λ_d at 15GHz), and they are connected together using metal stripes patterned in the LTCC layers they go through. The stripes connecting the vias are separated by one 110µm-thick layer of LTCC (ca. 1/66λ_d at 15GHz). This implementation of the side-walls of the cavity using a two-dimensional grid aims at the realisation of electrical boundaries, which are as dense as possible to prevent the electromagnetic field from fleeing outside the cavity. The cavity is five 110µm-thick LTCC layers deep (550µm). The input and output couplings of the cavity resonator mounted in transmission are realised using a so-called "coupling via" connecting the input and output microstrip lines to the bottom of the cavity. See Figure 1.

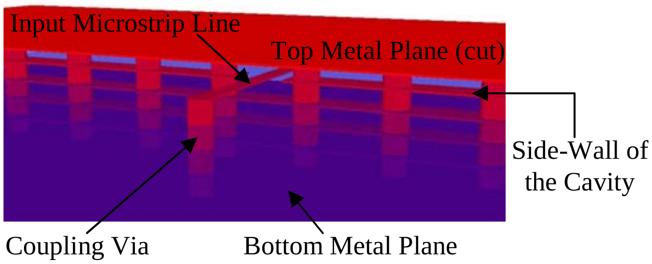

Figure 1. 3D-View of the structure used for the input\output couplings.

The coupling realised in this way is inductive and its strength is determined by the distance, noted *a*, between the coupling via and the adjacent side-wall of the cavity. The external Q-factor of the doubly terminated cavity resonator has been simulated using the full-wave commercial simulator EMPIRE for different positions of the via inside the cavity. These values are plotted against the relative position of the via in Figure 2.

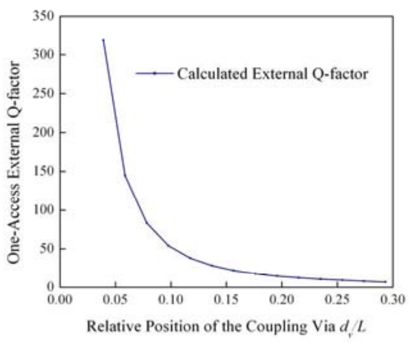

Figure 2. Value of the one-access external Q-factor versus via position

The via position is normalised to the length, *b*, of the cavity resonator such that a ratio *a*/*b* equal to 0.5 corresponds to a via placed at the centre of the cavity. In order to measure accurately the unloaded Q-factor of the proposed substrate integrated cavity, a weakly coupled cavity resonator has been fabricated and characterised. The base of the cavity resonator is chosen to be square to maximise its unloaded Q-factor. The S_{21} parameter of the measured cavity response is shown around the resonance in Figure 3.

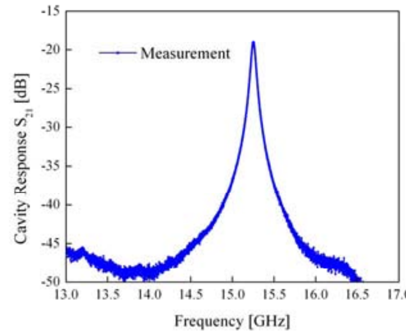

Figure 3. Measured resonance peak of the weakly coupled substrate integrated cavity resonator.

The resonance frequency of the cavity resonator is 15.25GHz. The unloaded Q-factor, Q_u, extracted from the measured S_{21} parameter according to the method proposed in [4] is Q_u=290. This value is limited by the different lossy mechanisms existing in the cavity resonator: the ohmic loss due to the finite conductivity of the Au-paste (σ=4.09e7 S/m, Q_o=497), the roughness of the structures patterned in LTCC (R_a=0.6-1µm), and the dielectric loss due to the tanδ of the LTCC material (tanδ=0.0015, Q_d=666). The power dissipated through the non-fully metallised side-walls of the cavity resonator has been assessed by the measurement of two identical cavity resonators having one and two rows of vias, respectively. The difference between the unloaded Q-factors measured in both cases is extremely small and it can be assumed that this phenomenon is negligible for the geometry of the two-dimensional grid described above. In return, this implementation of the side-walls results in a larger effective surface of the cavity walls and increases the ohmic loss in comparison to the standard waveguide cavity resonators. The theoretical unloaded Q-factor of the substrate integrated cavity resonator calculated from the ohmic and dielectric losses is 269.

III. 2-Pole Substrate Integrated Cavity Resonator Filter

The 2-pole filter is realised with two substrate integrated cavity resonators coupled together by an inductive iris. The iris is implemented by an opening in the inter-cavity wall. Due to the diameter of the vias of 150µm and because of the minimal width of the metal stripes connecting the vias (222µm), the inductive iris cannot be supposed infinitely thin. For design purpose, the values of the impedance inverter *K* achieved for different widths of the thick iris have been calculated from the simulated S_{21}-parameter of the two-port discontinuity. The input and output couplings of the filter are achieved using the same structure as the one presented to couple the doubly terminated cavity resonator. A 3D-view of the filter is shown in Figure 4.

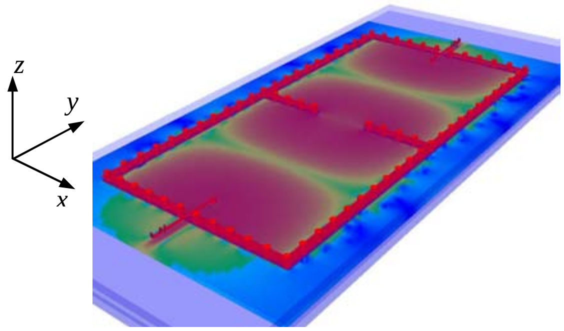

Figure 4. 3D-View of the 2-pole filter (top metal plane removed) with the Hx-field component at 15GHz.

The coefficients to achieve for the coupling between the cavity resonators and in input and output of the filter are determined from the low-pass to band-pass transformation of a low-pass prototype filter [5]. The value of the external Q-factors $(Q_e)_1$ and $(Q_e)_2$ as well as the coupling coefficient k_{12}, with which the two cavity resonators have to be coupled are given in Table II.

TABLE II. COUPLING COEFFICIENTS OF THE 2-POLE FILTER

Parameter	Value
$(Q_e)_1$	26.51
k_{12}	0.0377
$(Q_e)_2$	26.51

The entire filter has been optimised using full-wave simulations for the geometry of the coupling structures as well as for the length of the cavity resonators. A photograph of the filter realised in LTCC is shown in Figure 5 and the measured S_{11} and S_{21} parameters of the filter response are plotted in Figure 6.

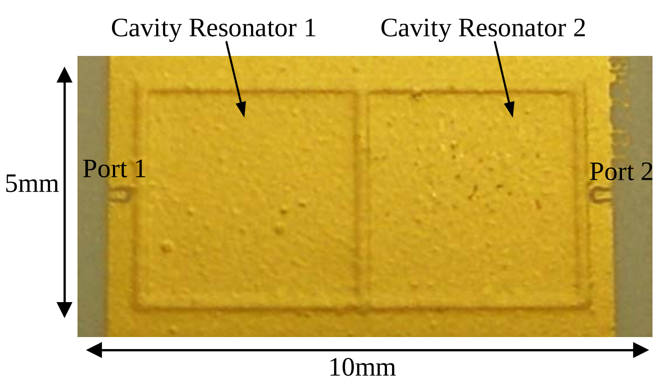

Figure 5. Photograph of the substrate integrated 2-pole filter

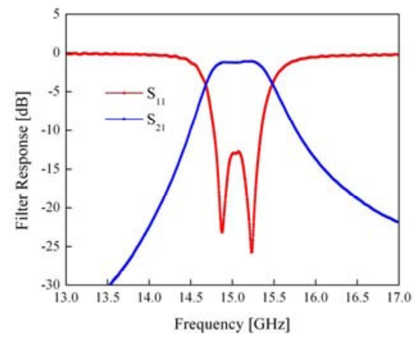

Figure 6. Measured response of the 2-pole substrate integrated cavity resonator filter.

The centre frequency and the –3dB bandwidth of the measured filter response are 15.09GHz and 813MHz (5.39%), respectively. The –24dB of attenuation required at 12.6GHz are more than achieved and the return loss is better than –13.8dB in the pass-band. The in-band insertion loss measured at 1.04dB is above the loss level given in the specifications. This limitation of the filter proposed here is due to a too low unloaded Q-factor of the substrate integrated cavity resonators and cannot be solved directly by a re-design of the filter. To overcome this situation and if the loss budget attributed to the filter cannot be relaxed, other resonator topologies like air-filled cavity resonator have to be considered.

IV. BST-VARACTOR BASED TEMPERATURE COMPENSATED CAVITY RESONATOR

In order to investigate the behaviour of the resonance frequency of LTCC cavity resonators when the temperature of the substrate increases, the weakly coupled cavity resonator presented in section I has been measured between room temperature (30°C) and 120°C. The relative variation of the resonance frequency is plotted versus temperature in Figure 7.

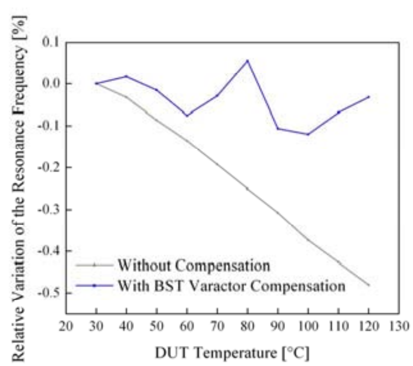

Figure 7. Relative shift of the resonance frequency measured over temperature for cavity resonators with and without compensation.

The measured resonance frequency of the cavity resonator assumes a variation of –4.8% over 90°C with an almost constant slope of –54.2ppm/°C. This down-shift of the resonance peak can be explained by two mechanisms: the mechanical dilatation of the geometry of the cavity due to the Thermal Coefficient of Extension (TCE) of the LTCC DuPont 943 material given at 6ppm/°C, and the variation of the relative dielectric constant of the substrate with the temperature. The temperature coefficient of ε_r calculated from the TCE of DuPont 943 and from the frequency shift actually measured for the cavity resonator is 95.2ppm/°C. In order to compensate this frequency shift of the cavity resonator, a solution implementing a ferroelectric varactor coupled to the cavity resonator has been investigated. The varactor is coupled to the cavity using a coupling structure similar to the one presented for the input/output couplings of the cavity resonator presented in section I. Nevertheless, here the coupling via connects the bottom of the cavity to a conductor realised on the top of the cavity and forming a coplanar line with the top metal plane. The varactor, fabricated by EPFL, is a BST (Barium Strontium Titanate) varactor realised on LAO substrate. It is integrated in a hybrid fashion on the LTCC substrate in a two-LTCC-layer-deep cavity realised close to the cavity resonator. Figure 8 shows the integration concept of the ferroelectric varactor on the LTCC substrate.

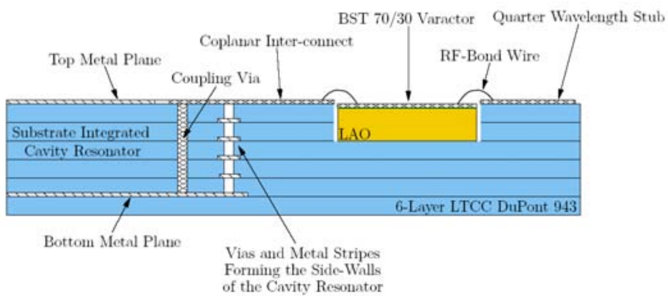

Figure 8. Hybrid integration concept of the BST-varactor on the LTCC substrate

The principle used for the compensation of the frequency shift is based on the temperature-dependent behaviour of the BST-varactor. The BST film used for the ferroelectric-varactor is temperature sensitive and the value of its dielectric constant decreases by 52% between 30°C and 100°C. This variation of the relative permittivity results in a change of the capacitance, which assumes, at 100°C, only 42% (ca. 122pF) of the value it has at room temperature (ca. 290pF). For a suitable strength of the coupling between the cavity resonator and the ferroelectric varactor, the down-shift of the resonance frequency can be compensated by the temperature-dependent capacitor over a defined temperature range. The BST-varactor temperature-compensated cavity resonator has been designed, realised and characterised between 30°C and 120°C. A photograph of the device is depicted in Figure 9.

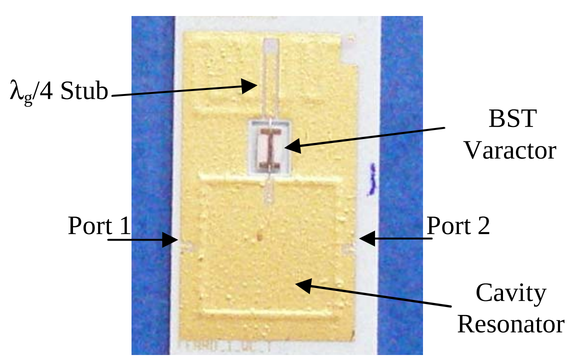

Figure 9. Photograph of the temperature-compensated cavity resonator.

The relative shift of the resonance frequency of the temperature-compensated resonator is plotted together with the one of the original cavity in Figure 7. The resonance frequency of the compensated resonator is much more constant over temperature than the one of the un-compensated resonator. It assumes a shift of -0.03% between 30°C and 120°C with a peak at -0.12% at 100°C.

Finally, the unloaded Q-factor of the compensated cavity resonator has been extracted from the measured S_{21}-parameter. The unloaded Q measured at 63.3 is lower than the Q_u=290 obtained for the un-compensated resonator. This reduction of the unloaded Q-factor is due to the additional ohmic and dielectric losses in the inter-connects used to couple the varactor and in the varactor itself.

V. Conclusions

The paper describes the design, the realisation and the measurement of a two-pole substrate integrated cavity resonator filter made out of low-loss LTCC DuPont 943 material. The proposed filter assumes a response centred at 15.09GHz, a –3dB bandwidth measured at 813MHz (5.39%) and about 1dB for the in-band insertion loss. The characterisation over temperature of a cavity resonator integrated in LTCC has highlighted a down-shift of the resonance frequency of -4.8% between 30°C and 120°C. To overcome this situation, a solution using a ferroelectric varactor coupled to the cavity resonator is assessed. The proposed compensation technique allows for a more stable behaviour over temperature of the cavity resonator and brings the frequency shift down to -0.12% over the same temperature range.

The work presented in this paper constitutes the first development step toward a more sophisticated frequency-agile and temperature-compensated filter intended for UAV military data link.

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