RF-MEMS Tunable Filters on Low-Loss LTCC Substrate for UAV Data-Link

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***Abstract*— In this paper, a fixed-frequency filter and two RF-MEMS based frequency-agile filters at Ku-band are demonstrated. All filters are designed in a so-called Substrate Integrated Cavity (SIC) topology, and they are processed in LTCC (Low Temperature Co-fired Ceramics) DuPont 943 substrate. The tunable filters are steered over frequency by means of coplanar stubs, whose electrical length is adjustable. The tunable stubs are RF-MEMS cantilevers processed on silicon. The paper describes the design of the fixed and tunable filters, and it proposes a hybrid integration concept of the silicon chips onto the ceramic board of the filters. Finally, all presented structures are characterised by on-wafer measurements, and they are assessed in regard to the expected performance.**

I. Introduction

The fixed-frequency and tunable filters presented in this paper have been developed for Unmanned Air Vehicle (UAV) data-link at Ku-band. They are foreseen for integration on both sides of the communication link: on-board of UAVs, and in the control station on ground. In those systems, they aim at replacing inter-digital cavity filters, which have been successfully implemented in the last decade and up to now. Nevertheless, these filters, used as Local Oscillator (LO) filters, are the largest components of the front-end, and they represent a bottleneck preventing a further size reduction of the complete system. As the next generation of products will require improved performance and reduced size, the new filters have been chosen to be realised in LTCC. LTCC technology allows for 3D-integration of different components that can be integrated monolithically, or in a hybrid fashion into a same ceramic board. Also, it offers the advantage of being low-cost for large production scales. Further, thanks to the recently developed low-loss ceramic tapes like DuPont 943, satisfactory RF-behaviour can be expected for the filters.

However, expectations for the next generation of front-ends are not limited to a size reduction, and more and more, the re-configurability of communication systems becomes a major preoccupation. The trend is now to evolve toward flexible systems capable of handling multi-function data-link operating in different frequency bands. For this reason, the development of frequency-agile filters, which are key components of reconfigurable front-ends, turned out to be one of the most exciting challenges in the past few years.

The electrical specifications of the fixed and tunable filters are defined, between others, by the width of the communication channels implemented for the data-link. They are listed in Table I for both filters.

TABLE I
Specifications of the Fixed and Tunable Filters

Parameter	Fixed	Tunable State 1	Tunable State 2
Centre Frequency	F_0 GHz	F_{t1} GHz	F_{t2} GHz
-3dB bandwidth	0.8 GHz	0.8 GHz	0.8 GHz
In-Band IL	<0.5 dB	<0.5 dB	<0.5 dB
In-Band RL	<-16 dB	<-16 dB	<-16 dB
Out of Band Rejection			
F_{OBR1} GHz	<-24 dB	<-24 dB	--
F_{OBR2} GHz	--	--	<-24 dB

An important requirement of tunable filters is the tuning range. In the case addressed here, it is defined by $\Delta F = F_{t2} - F_{t1}$, and it is equal to 400MHz (2.6%). Further, a minimum attenuation level is specified at one specific frequency noted F_{OBR1} and F_{OBR2}, for the fixed-frequency filter and for the two states of the tunable filter. These frequencies are 16% below the centre frequency of the respective filters. They aim at filtering out the second harmonic generated by the LO of the transceiver.

II. Fixed-Frequency Substrate Integrated Filter

The fixed-frequency band-pass filter is realised with two inductively coupled cavity resonators. The cavity resonators are realised in LTCC according to the Substrate Integrated Waveguide (SIW) concept [1], [2]. Each cavity resonator is closed on its top and bottom sides by fully metallised planes processed in LTCC. The side-walls of the cavities are designed using rows of vias manufactured in LTCC. The pitch between two consecutive vias is 513µm (approx. $\lambda_d/14$ at F_0). They are connected together using metal stripes patterned in the LTCC layers which they go through. The stripes connecting the vias are separated by one 110µm-thick layer of LTCC (approx. $\lambda_d/66$ at F_0). This implementation of the side-walls with 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 cavities are deep of five LTCC layers (550µm).

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The filter has been designed using the low-pass to band-pass transformation technique [3]. It is a 2-pole Tchebycheff filter with 0.5dB of in-band ripple. The coefficients of the low-pass prototype filter as well as the electrical parameters of the band-pass filter are summarised in Table II.

TABLE II
ELECTRICAL PARAMETERS OF THE FIXED-FREQUENCY FILTER

Parameter	Value
Low-Pass Prototype Filter	
(g_0; g_1; g_2; g_3)	1; 1.4029; 0.7071; 1.9841
Band-Pass Filter	
$(Q_e)_A$, $(Q_e)_B$	42.512
$X_{1,2}/Z_0$	0.1063

The input/output coupling structures are realised with microstrip lines buried one LTCC layer below the metal plane closing the cavity on its top side. Also, the ground plane of these microstrip lines is formed by an extension of that same metal plane. The lines are lead into the cavity resonator through an opening (mouse-hole) realised in the via row forming the side-wall of the cavity. The coupling itself is achieved using a via processed inside the cavity resonator and connected to the microstrip line. This so-called "coupling via" is parallel to the side-wall of the cavity resonator, and it is realised between the end of the input/output lines and the bottom of the cavity (Fig. 1).

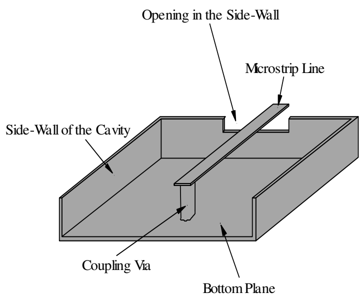

Fig. 1 3D drawing of the input/output coupling structures of the substrate integrated cavity (top plane removed and side-walls idealised).

This structure might be designed for different configurations of the coupling via. Depending on the strength of the coupling to achieve, the via can be long (up to 440µm) or short (no via), and it can be placed far away from the side-wall, or at a modest distance of it. In order to reduce the number of configurations to investigate, the maximal length (440µm) has been chosen for the coupling via, which, in that case, connects the bottom of the cavity to the buried microstrip line. This configuration has been adopted because it allows for a very wide range of achievable coupling coefficients. The length of the coupling via being fixed, the input/output coupling coefficients are uniquely controlled by the position of the via in the cavity resonator.

The 2-pole filter is realised with two substrate integrated cavities juxtaposed in such a way that they have exactly one side-wall in common. The two cavities are coupled together through an inductive iris opened in the row of vias forming the inter-cavity wall, similar to irises implemented in waveguide filters. However, due to the diameter of the vias, and more importantly to the width of the metal stripes connecting them (approx. 200µm), the iris realised in that way is thick. For this reason, the coupling achieved with such an iris is weaker than the one that would be obtained for a thin iris having the same aperture. In order to determine the value of the coupling coefficient versus the width of the iris, the S_{21}-parameter of that thick iris has been simulated for various openings. Finally, the complete 2-pole filter has been optimised using the full-wave commercial simulator EMPIRE. A 3D-view of the 2-pole substrate integrated filter showing the H_x-field component is depicted in Fig. 2.

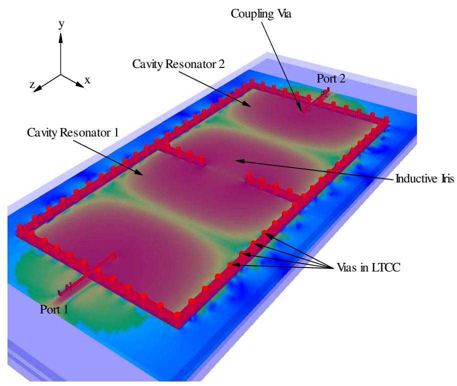

Fig. 2 3D-view of the fixed-frequency substrate integrated cavity filter (top plane removed)

In order to measure the filter using 250µm-pitch coplanar measurement probes, a buried microstrip line to coplanar transition has been designed. The response of the 2-pole Tchebycheff filter measured using SOLT calibration, and including the input/output transitions is plotted in Fig. 3.

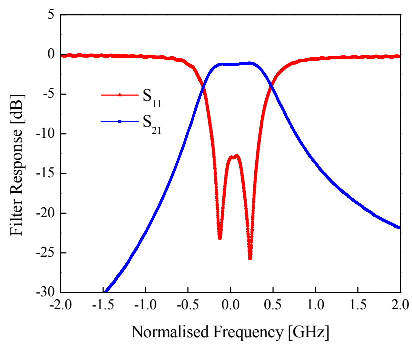

Fig. 3 Measured response of the fixed-frequency filter.

The measured filter response has a pass-band centred 0.6% above the targeted centre frequency F_0, and the -3dB bandwidth is 813MHz (5.39%). It is 13MHz wider than the required bandwidth specified at that same level. These slight inaccuracies observed for the design are attributed to a possible uncertainty about the value used in the simulation for the dielectric constant of the LTCC substrate. Finally, the return loss are better than -13.8dB, and the minimum in-band insertion loss is about 1dB. From [3], this level of in-band insertion loss corresponds to an unloaded Q-factor of 160 for the two substrate integrated cavity resonators.

III. RF-MEMS Frequency-Agile Filters in LTCC

The fixed-frequency filter demonstrated above is used as starting point for the development of the frequency-agile filter. The tunable filter, which is a 2-pole filter as well, aims at the same response as the fixed-frequency filter, but tunable in one 400MHz-step. Nevertheless, in order to assess the advantages and limitations of the proposed tuning concept, two frequency-agile filters are proposed in the coming sections. The two tunable filters are based on a unique principle, but they are designed to achieve different tuning ranges.

A. Design of the Frequency-Agile Filters

The filter response is made steerable by means of adjustable lines coupled to each one of the substrate integrated cavity resonators [4]. The adjustable lines are coplanar lines open-circuited at one end, and inductively coupled to the cavity resonator at the other end. They are designed on top of the filter, at the same level than the metal ground plane closing the cavity on its top side. Thanks to RF-MEMS cantilevers connected to the coplanar lines on LTCC, additional lengths of stub can be connected to the lines coupled to the cavity resonator. Also, depending on the electrical length of that adjustable stub, the reactance coupled to the cavity resonator can be capacitive or inductive, and it may take different values changing the behaviour of the resonator around the resonance. The variable impedance, noted $Z_{var}{=}jX_{var}$, generated by the stub, and loading the cavity is connected in parallel with the series RLC-resonance of the cavity resonator. The schematic of a 2-port tunable cavity resonator is shown in Fig. 4.

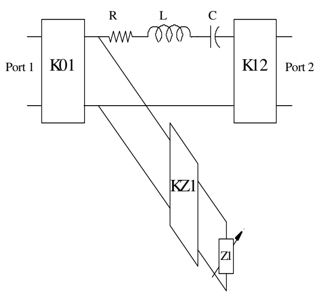

Fig. 4 Schematic of a frequency-agile cavity resonator.

The tunable impedance Z_{var} seen by the cavity resonator is the impedance Z_l achieved in input of the adjustable stub after it is transformed by the impedance inverter KZ_l. The values of the variable impedance Z_l are calculated so that the resonance frequency of the resonator is shifted away from its TE_{101} resonance, when the length of the stub varies. If the electrical length of the adjustable stub is shorter than a quarter wavelength, the reactance X_{var} coupled to the cavity resonator is inductive and the resonance is shifted downwards. In return, if the electrical length of that same adjustable stub is longer than a quarter wavelength, X_{var} is capacitive, and the resonance frequency is shifted upwards. According to this, the tuning range that can be reached depends on the values achievable for the variable reactance. Nevertheless, in order to increase the tuning range, several adjustable stubs can be implemented for each cavity resonator. In this case, the variable reactances provided by the different adjustable stubs are in parallel, and they result in a larger overall on/off ratio. This technique with several adjustable stubs is however at the price of increased power loss dissipated in the additional tunable lines.

B. Hybrid Integration of the RF-MEMS Adjustable Stubs

The RF-MEMS circuits used to tune the resonance frequency of the filters are processed on 300µm-thick high-resistivity silicon wafers. The silicon chips are integrated in a hybrid fashion onto the ceramic substrate, where the filters are fabricated. The chips are placed in cavities processed approximately 200µm away from the cavity resonators of the filters. The structures patterned on the silicon chips are connected to the coplanar lines on LTCC by means of Al bond wires. These bond wires are kept as short as possible by choosing a three LTCC layer depth (approx. 330µm) for the cavities in LTCC. This depth compensates well the thickness of the silicon chips, once they are fixed with about 100µm of conductive glue. A cross-sectional drawing of the hybrid integration of the RF-MEMS chips is depicted in Fig. 5.

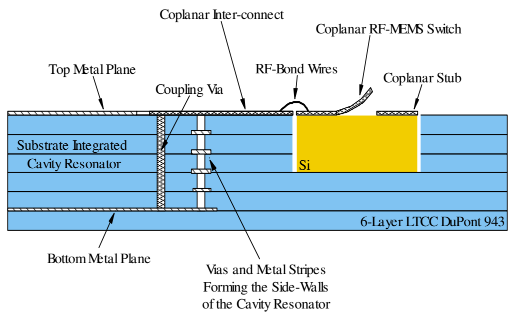

Fig. 5 Hybrid integration concept of the RF-MEMS structures onto the ceramic substrate.

Due to the hybrid integration of the RF-MEMS structures, the adjustable stubs are formed by two parts processed separately and in parallel: directly on top of the LTCC substrate for one part, and on the silicon chips for the other part. The tunable stubs are inductively coupled to the cavity resonators through coupling vias similar to the ones introduced for the input/output couplings. In this case, however, they are 550µm-long because they go all the way through the cavity. This is necessary because the tunable stubs are designed on the uppermost metal layer, on top of the LTCC substrate. Two filters have been realised with one and two adjustable stubs per cavity resonator, respectively. A photograph of the filters is shown in Fig. 6.

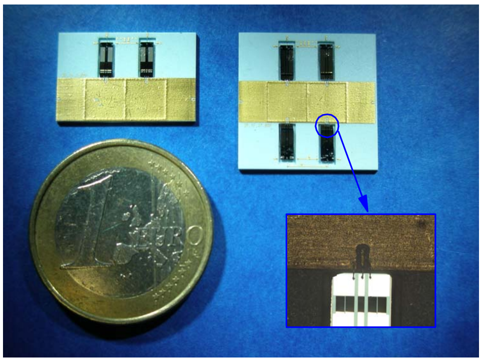

Fig. 6 Photograph of the frequency-agile filters.

C. *Characterisation and Measurements*

The tunable filters have been measured using a measurement setup similar to the one used to characterise the fixed-frequency filter. For these filters, however, the on-wafer measurement table was equipped with a DC-wedge enabling the control of the RF-MEMS devices. The responses of the two tunable filters are plotted for the different switching states of the RF-MEMS circuits in Fig. 7 and 8.

The graphs show well-formed filter transfer functions tuned over 3% (446MHz) for the filter with one adjustable stub, and over 7.2% (1077MHz) for the filter with two adjustable stubs. The -3dB bandwidths measured for the filters are rather constant, when the responses are steered. However, the responses plotted in Fig. 8 are slightly narrower (about 4.3%) than the ones measured for the first filter: 4.7% (711MHz) in the up-state, and 4.9%(728MHz) in the down-state. Finally, the insertion loss has been measured at -3.1/-4.0dB and -5.7/ -5.0/-4.7dB for the different states of the first and the second filter, respectively. This in-band insertion loss is above the 0.5dB of loss allowed for the filter. It is also logically larger than the insertion loss measured for the fixed-frequency filter. This is explained by the additional loss dissipated in the planar transmission lines on both, the LTCC and the silicon chips.

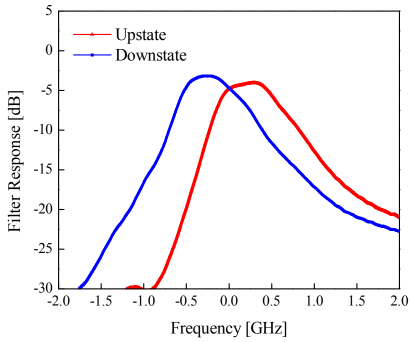

Fig. 7 Measured response of the frequency-agile 2-pole filter with one adjustable stub per cavity resonator.

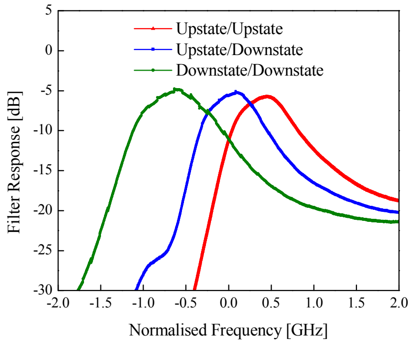

Fig. 8 Measured response of the frequency-agile 2-pole filter with two adjustable stubs per cavity resonator.

A limitation of the tuning concept presented here is the presence of parasitic resonances in the neighbourhood of the pass-band. These resonances (not visible on the plots) arise approximately 20% below and above the pass-band. Their magnitudes depend on the coupling coefficients between the cavities and the adjustable stubs.

IV. Conclusions

This paper has presented the design, the realisation, and the measurement of fixed and RF-MEMS based frequency-agile LTCC filters. The RF-MEMS circuits necessary to tune the filters are processed in silicon technology. They are integrated in a hybrid fashion in cavities manufactured in the LTCC substrate of the filters. Satisfactory on-wafer measurement validates the concept implemented to tune the filter response, and a honourable tuning range of 7.2% has been demonstrated. Beyond this, the concept shows also some limitations especially in terms of insertion loss. The work presented here is to be continued further with an optimisation of the tuning structures. It constitutes the first step of a longer project aiming at low-loss and low-cost frequency-agile filters for spaceborne and airborne applications.

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