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Additional Information

Miniaturized Ultra-Wideband Bandpass Filter Based on Substrate Integrated Quasi-Lumped Resonators

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Abstract—A compact ultra-wideband bandpass filter employing substrate integrated quasi-lumped resonators is presented in this paper. A multi-layer hybrid structure is proposed, combining quasi-lumped resonators and surface mount components. This allows a huge miniaturization degree due to the high capacitive loading. Moreover, strong magnetic and electric couplings can be implemented thus enabling the introduction of transmission zeros for improving response selectivity. A filter example centered at 5.35 GHz with a prescribed channel bandwidth of 2.9 GHz has been designed, manufactured and measured. The filter size is smaller than $7 \times 7 \text{ mm}^2$. The obtained results show the feasibility of the proposed approach.

Index Terms—Substrate integrated waveguide (SIW), ultra-wideband, mixed coupling, miniaturization.

I. INTRODUCTION

Wideband filters are essential components for emerging flexible payloads as they are required at the RF/IF frequency conversion stages for Nyquist band selection [1]. Nevertheless, new applications such as nano- or pico-satellites are demanding a higher degree of miniaturization while keeping very stringent electrical specifications. Filters in strictly planar technology have a low manufacturing cost, small size, and are easy to implement for mass production. However, they suffer from a lower quality factor compared to waveguide implementations. On the other hand, Substrate Integrated Waveguide (SIW) technology [2] could be a good alternative, as they maintain a moderate-to-high quality factor while being significantly smaller and lighter. However, although some compact implementations have been proposed, they are still relatively large in size compared to microstrip technology and further miniaturization is not straightforward.

In this paper, a substrate integrated filter is proposed based on a quasi-lumped implementation of a coaxial SIW filter [3]. This approach enables to drastically reduce the device size, while providing additional degrees of freedom for designing and post-manufacturing tuning, which is also critical for high-end filter implementations.

II. RESONATOR STRUCTURE

The basic structure of the quasi-lumped substrate integrated resonator was already presented in [4] and it is shown in

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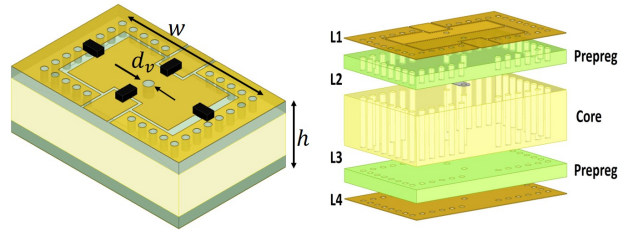


Fig. 1. Scheme of a single resonator (left) and substrate stack-up (right).

Fig. 1. A rectangular patch is isolated from the top ground plane through a capacitive gap. The patch is short-circuited to the bottom ground plane using a plated via hole. If $h \ll \frac{\lambda}{4}$, the inner via hole and the cavity walls behave as an electrically short embedded transmission line of length h (i.e. substrate thickness) and admittance Y_0 . The admittance is given by the ratio between the via hole diameter d_v and the distance to the cavity walls w .

Usually, there are two ways of controlling the resonant frequency of the resonator. Firstly, the capacitive loading can be modified by increasing or decreasing the isolating gap width. Moreover, it is possible to control the inductive part of the resonator by adjusting the diameter of the plated via hole d_v for a given resonator width w . Of course, minimum values for these parameters are determined by the manufacturing process, thus limiting the degree of miniaturization of the structure.

Further compactness can be achieved by adding extra capacitive loading to the basic structure. Thus, lumped capacitors have been connected from the resonator patch to the adjacent ground plane as can be seen in Fig. 1. This provides two important advantages:

- 1) Additional miniaturization due to the availability of ultra-small surface mounted device (SMD) capacitors with high capacitance values (i.e. $> 1 \text{ pF}$).
- 2) Post-manufacturing tuning abilities enabled by the optimization of the capacitor values for a fixed resonator structure.

Therefore, considering C_r as the total resonator capacitance given by the addition of the patch contribution and the assembled SMD capacitors, the susceptance of the resonator can be expressed as

$$B(\omega) = \omega C_r - Y_0 \cot \beta h \quad (1)$$

where β is the propagation constant of the quasi-lumped piece of transmission line. This part can be modeled as a lumped inductor given by the inner conductor separated at a distance $w/2$ from the cavity walls [4].

$$L_r = \frac{\eta_0 h}{2\pi c_0} \ln \frac{4W}{\pi d_v} \quad (2)$$

where c_0 is the speed of light in vacuum and η_0 the wave impedance in free space. The resonant frequency can be obtained from $B(\omega_0) = 0$.

III. ULTRA-WIDEBAND FILTER DESIGN

Bandpass filters using the previous resonator cell can be designed by properly coupling several resonators following an in-line configuration. However, in order to design an ultra-wide band filter, very high coupling values are required. Moreover, a broad control of the resonant frequency is also needed to reach the desired response. In this work, several SMD components have been included in the structure in a hybrid way to solve these problems. Then, the design of a practical filter follows an approach similar to the one employed for designing a conventional coupled-resonator filter structure.

A. Resonant frequency

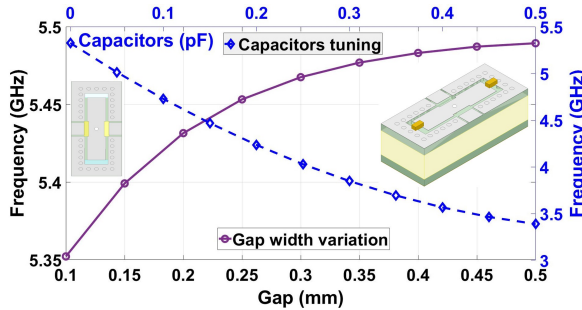


Fig. 2. Resonant frequency as a function of the gap width (black) and tuning capacitors (blue). A gap width of 0.1 mm has been considered for the analysis of the variation with the SMD capacitors.

There are two main mechanisms for controlling the resonant frequency of each resonator. Firstly, for a given cavity size w , the gap between the top ground plane and the rectangular patch can be modified. This allows to finely control the center frequency. However, in order to significantly reduce the resonant frequency, two SMD capacitors have been assembled at both ends of the resonator patch as it is shown in Fig. 2. As can be seen, a very large tuning ratio can be achieved without modifying the layout of the structure.

B. Input/output coupling

The input/output coupling (given by the external quality factor Q_{ext}) has been implemented by means of a coplanar probe penetrating the capacitive gap of the first/last resonator as it is shown in Fig. 1. The insertion length of the probe

enables to control the coupling level. This value can also be boosted by mounting an additional SMD capacitor at the top layer between the probe end and the resonator patch. The Q_{ext} can be easily extracted by using a well-known approach based on the group delay response [5].

C. Inter-resonator coupling

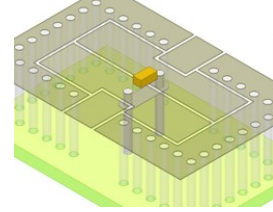


Fig. 3. Mixed inter-resonator coupling obtained from the capacitive gap in the top layer with an increase due to the SMD capacitance (electric coupling) and the short circuit between the two plated inner via holes (magnetic coupling).

Due to the huge bandwidth required, a strong inter-resonator coupling is absolutely required. Moreover, in order to introduce transmission zeros that improve the selectivity of the filter, a mixed-coupling approach has been implemented. Thus, capacitive coupling is provided at the top layer by controlling the distance between resonator patches. This electric coupling level can be also increased by mounting SMD capacitors between adjacent resonators. For implementing a mixed coupling, a strong magnetic contribution has been introduced by short-circuiting the inner conductor of adjacent resonators [6]. This cannot be done at the top layer and it requires a multi-layer implementation of the structure. Therefore, an inner conductor layer needs to be added in order to implement the connection between the plated via holes as can be seen in Fig. 3.

This mixed coupling also enables to introduce two transmission zeros in the upper band, which can be controlled independently by the SMD capacitors used for coupling between resonators 1-2 and 3-4, or by the width of the magnetic short-circuit created at the inner layer. SMD capacitors mounted on the gap enables us to adjust the coupling value.

D. Filter design

A 4th order Chebyshev filter centered at 5.35 GHz with a bandwidth of 2.9 GHz (FBW = 54.2%) and minimum in-band return loss of 15 dB has been designed, fabricated and measured following the proposed approach. The device must also provide rejection higher than 30 dB at the lower stopband and higher than 20 dB at the upper side.

It has been implemented in a 4-layer PCB stack-up consisting on a core of 1.524 mm-thick RO4003C ($\epsilon_r = 3.55$, $\tan \delta = 0.0027$) with two 0.404mm-thick RO4350B ($\epsilon_r = 3.55$, $\tan \delta = 0.0037$) pre-preg layers. Both internal and external Cu layers have a thickness of 17 μm . The top layer has been used for resonator design and components assembly, while layers 2 and 3 are used for implementing the strong inter-resonator magnetic coupling. The bottom layer is the ground plane of the structure. A scheme of the stack-up is

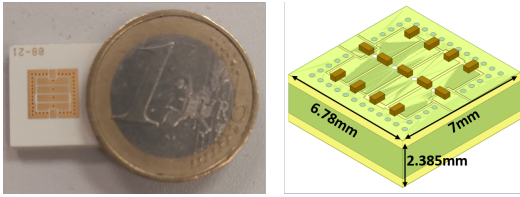


Fig. 4. Filter prototype before capacitor integration (left) and scheme of the structure (right).

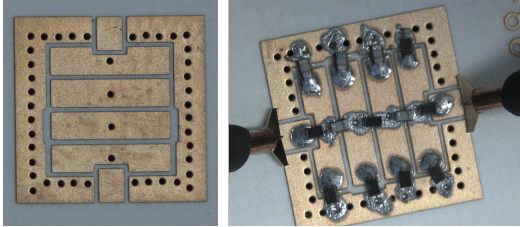


Fig. 5. Optical microscope photography of the fabricated device (left) with mounted SMD capacitors (right).

shown in Fig. 1. Firstly, an initial synthesis of the structure has been performed following the classical approach of an inverter-coupled resonator filter [7]. An equivalent circuit has been implemented including the lumped capacitors for resonant frequencies, input/output and inter-resonator coupling control. The value of all capacitors has been optimized at circuit-level in order to satisfy the filter specifications and improve rejection by properly locating the transmission zeros. Each individual cavity has a width of $W = 5.7$ mm. The inductive metallic holes were fixed at the minimum diameter allowed by the manufacturer (i.e., $d_v = 250$ μm). The equivalent inductance of a single cavity results in $L \approx 1.6$ nH (2) that gives a gap capacitance of $C_{\text{gap}} \approx 0.55$ pF. Loading capacitances of 0.05 pF have been mounted on the cavities, while values going from 0.3 to 0.6 pF have been used for the couplings. The size of the structure is about 7×7 mm², showing a huge degree of miniaturization at C-band. Full-wave EM simulation results of the designed structure including the real models of the SMD capacitors are shown in Fig. 6.

IV. EXPERIMENTAL VERIFICATION

The filter has been manufactured using a 4-layer standard PCB process in Rogers RO4003C/RO4350B materials. A photo of the fabricated device with the assembled components is shown in Figs. 4 and 5. The SMD capacitors mounted on the top layer are thin-film devices from AVX Accu-P 0201 series. Experimental results are depicted in Fig. 6. Insertion loss at center frequency is 0.75 dB while in-band return loss level is better than 14 dB. As can be seen, a slight frequency shift is present, resulting in a higher filter bandwidth. This deviation is due to the combination of the manufacturing and capacitor tolerances. A back-simulation using the equivalent circuit model of the filter for extracting the actual values of the loading capacitance for each resonator has been performed. As can be seen in Fig. 6, the measured response can be recov-

ered with a very good agreement by considering the actual capacitance value of each resonator and coupling. Deviations from 25 to 150 fF have been obtained. Therefore, corrections can be applied to the SMD capacitors used in order to correct the response and satisfy the specifications.

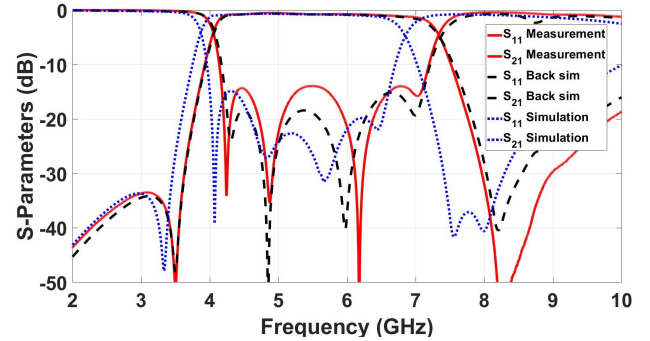


Fig. 6. Simulated (blue), measured (red) and back-simulated (black) S-parameters of the filter.

V. CONCLUSION

A miniaturized 4th-order ultra-wideband bandpass filter in quasi-lumped substrate integrated technology has been proposed in this paper. SMD capacitors integrated on the top layer enable us to reduce the filter dimensions, resulting in an extremely compact structure. In order to increase the filter bandwidth, a strong magnetic coupling implemented using a multi-layer structure has been superimposed on the inter-resonator capacitive coupling. This mixed-coupling has been also employed for introducing transmission zeros improving the filter selectivity. Due to the hybrid nature of the structure, manufacturing and component tolerances can be easily compensated by adjusting the loading and coupling capacitor values. The proposed structure can be of great interest for implementing highly integrated filters for emerging flexible payloads.

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