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Resistorless Implementation of Lossy Filters Using Coaxial SIW Resonators With Non-uniform Q

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***Abstract*—A technique for designing bandpass filters with very flat amplitude response is presented in this paper. The approach is based on the use of non-uniform-Q resonators implemented in coaxial substrate integrated waveguide (SIW) technology. An important unloaded Q-factor ratio can be obtained by adequately controlling several layout parameters of the basic resonator cell, thus enabling to optimize the in-band response of the filter. The approach is experimentally demonstrated at X-band frequencies by designing two resonators in Rogers RO4003C ($\epsilon_r = 3.55$, $\tan\delta = 0.0027$) with unloaded Q-factors going from 53 to 270. Then, a 4th-order filter example with 2 transmission zeros is designed, fabricated and measured based on the former results. The filter is centered at 10 GHz with a 280 MHz bandwidth showing a in-band flatness better than 1 dB-pp, which would require an unloaded Q-factor about 600 for a uniform-Q implementation, therefore showing the advantages of the proposed approach for implementing bandpass filters for high-end RF and microwave applications.**

***Index Terms*—Bandpass filter, lossy filter, coaxial SIW, compact size.**

I. INTRODUCTION

In-band flatness requirements in high-end applications, such as satellite communications, pose enormous challenges to compact planar filter implementations due to the need of very high Q-factor resonators. Microstrip filter structures cannot usually reach the required flatness and/or rejection levels for narrow-band channel filters, while conventional substrate integrated waveguide (SIW) topologies are still limited by the inherent losses coming from the dielectric, as well as a larger footprint. Some low-loss implementations as air-filled [1] or empty SIW [2] could be an alternative at millimeter-wave frequencies, where device size is not critical anymore, but they still present evident inherent limitations in terms of batch manufacturing and integrability.

In order to improve the electrical response directly achievable with moderate-to-low Q resonators, lossy filter design techniques are a good alternative. Basically, the main idea consists on properly adjusting the filter response while introducing additional insertion loss within the passband. With the proper transformations, these losses can be adequately distributed among the resonators and couplings of the structure [3], [4]. However, the practical implementation is not straightforward, as resistors must be introduced at the required locations to obtain the requested losses.

In this paper, a bandpass filter based on resonators with non-uniform Q is presented in coaxial SIW technology. The main advantage is that the proper Q-factor required after the synthesis of the desired response can be implemented witout requiring any extra component. In Section II, the approach for finely controlling the Q-factor of coaxial SIW resonators is described and demonstrated experimentaly. Then, the application of this feature to the design of lossy filters with non-uniform Q resonators is presented in Section III. Experimental validation of a $4-$th order filter demonstrating the proposed approach is finally described in Section IV.

II. Q-FACTOR CONTROL IN COAXIAL SIW RESONATORS

Coaxial SIW resonators provide several degrees of freedom in the design process, all of them related to the different geometrical parameters involved in the structure. Although resonant frequency control and size miniaturization are usually the most relevant ones [5], these resonators provide also the possibility of a fine Q-factor control.

The general structure of a coaxial SIW resonator with its main design parameters is shown in Fig. 1. As it can be observed, the substrate thickness h plays a very important role for the physical and electrical performance, providing both miniaturization and higher unloaded Q-factor with larger thicknesses. However, the substrate thickness does not provide much flexibility to adapt the resonator Q-factor during the design process, as it is fixed and constant for all resonators of a particular topology. Other geometrical parameters are usually employed for controlling the resonant frequency, such as the capacitive gap s_P or the resonator admittance given by the cavity size $W_{\text{SIW}} \cdot L_{\text{SIW}}$.

However, the inner via hole diameter d_V and specially the patch size r_P, they allow a fine and constant control of the resonator Q by modulating the introduction of resistive losses associated to the loading capacitance.

As it is shown in Fig. 2, the simulated unloaded Q-factor Q_u changes both with d_V and r_P. However, it is evident that r_P provides a wider range of variation of Q_u values, while d_V has a minor effect being related to the inductive part of the resonator. As it is shown, the bigger r_P, the smaller the Q_u, being possible a reduction of Q_u of more than 80%. On the contrary, increasing d_V provides

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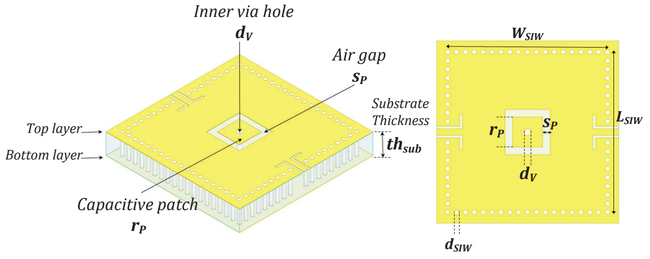


Fig. 1. 3D and top view of the coaxial SIW resonator.

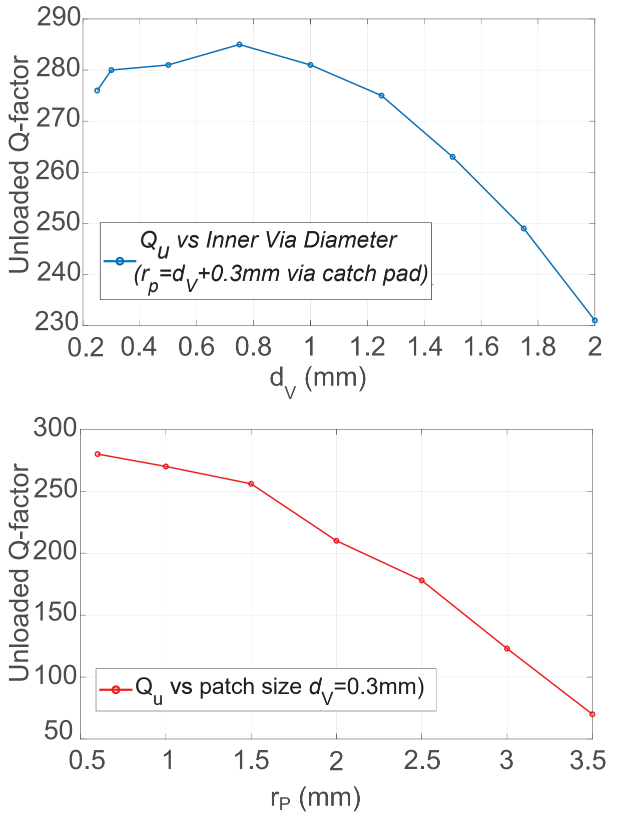


Fig. 2. Q_u-factor study of the coaxial SIW resonator: Q_u versus the diameter of inner via hole d_V (top), and Q_u versus the capacitive patch dimension r_P (bottom).

an enhancement of Q_u, but when it is necessary to have a larger patch to place the inner via, the effects of a bigger r_P, produces a higher Q_u reduction than the Q_u improvement of a bigger d_V. The main parameters of the resonator used in the study are: W_{SIW}=L_{SIW} $=$ 10 mm, h=1.524 mm-thick Rogers RO4003C substrate (ϵ_r=3.55, $\tan\delta$= $2.7 \cdot 10^{-3}$) with a finishing of 35 μm copper and 5 μm of Ni-Au.

With the aim to validate these concepts, two different resonators at $X-$band (i.e. f_0 $=$ 10 GHz) have been manufactured, one with a small patch (r_P=0.6 mm, W_{SIW}=L_{SIW}=10 mm; d_V=0.3 mm; s_P=0.23 mm) to reach higher Q_u values, and the other one with a large patch (r_P=3.872 mm, W_{SIW}=L_{SIW}=10 mm, d_V=2 mm; s_P=0.677 mm) to reach lower Q_u values. In Fig. 3, a photo of the manufactured resonators as well as their correspondent transmission responses are shown. For the coaxial SIW resonator with a large patch, the Q_u measured is 53, while for the resonator with small patch the extracted Q_u is 270. These measurements prove the wide range of possible Q_u values that can be obtained at practically the same resonant frequency with coaxial SIW resonators of the same cavity diameter.

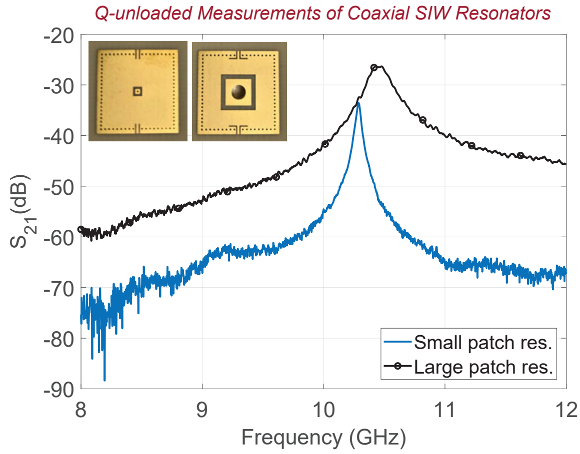


Fig. 3. Photographs and measurements of the manufactured coaxial SIW resonators.

III. FILTER DESIGN WITH NON-UNIFORM Q

The previously described feature can be used for implementing bandpass filters with very flat in-band response using non-uniform Q resonators. Thus, a fourth-order 18 dB return-loss Chebyshev filter has been designed. The center frequency is 10 GHz and its bandwidth 280 MHz. In order to improve the out of band selectivity, a pair of transmission zeros (TZs) close to the passband ($f_0 \pm 90\%$BW) have been introduced using a cross-coupling between resonators $1-4$. Then, by applying lossy techniques for the distribution of losses among the resonators [3], [4], an equivalent circuit has been synthesized by optimization. This process has taken into account the attainable low and high Q values. Thus, the high Q factor for inner resonators is optimized and limited to 270 (due to intrinsic dielectric and conductor losses), while the lower Q factor for first and last resonator is optimized to reach an in-band flatness better than 0.8 dBpp. Fig. 4 shows the coupling scheme and the structure of the designed filter, where its synthesis parameters and layout values are reported in Table I. Expressions for the synthesis of the remaining parameters of the coaxial SIW resonators can be found in [6].

The S-parameter responses of the synthesized and EM simulations are compared in Fig. 5a. As can be seen, both responses are in very good agreement. The insertion losses at f_0 are 3 dB. The return loss and flatness requirements are met and the narrow-band isolation for $f_0 \pm 100\% BW$, with the introduction of the TZs located at 9.58 GHz and 10.28 GHz, is higher than 20 dB. Moreover, in Fig. 5b are compared

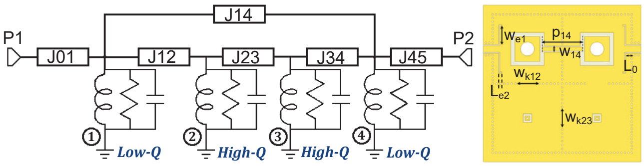
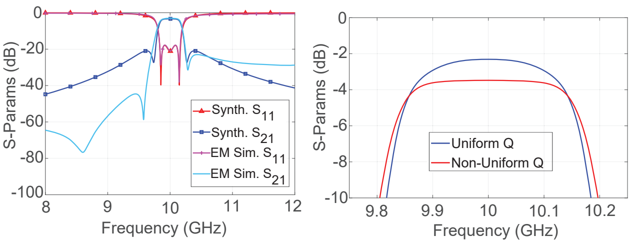


Fig. 4. Coupling scheme and structure of the non-uniform Q-lossy filter using coaxial SIW resonators.

TABLE I

VALUES OF THE DESIGN PARAMETERS OF THE NON-UNIFORM Q COAXIAL SIW FILTER"

Synthesis Value	Layout Dimensions [mm]
J_{01}=J_{45}=0.005616	L_0=1; w_{e1}=2.7; L_{e2}=0.293
J_{12}=J_{34}=0.0006206	w_{k12}=3.215
J_{23}=0.0004025	w_{k23}=2.994
J_{14}=−0.0003646	p_{14}=5.75; w_{14}=0.6
Low-Q Resonators (1 and 4) Q_u=82; b=0.0311; Z_0=53.7 Ω; θ_0=34.5	Low-Q Resonators (1 and 4) L_{SIW}=W_{SIW}=10; s_P=0.6; r_P=3.59; d_V=2
High-Q Resonators (2 and 3) Q_u=266; b=0.0146; Z_0=114 Ω; θ_0=34.5	High-Q Resonators (2 and 3) L_{SIW}=W_{SIW}=10; s_P=0.268; r_P=0.69; d_V=0.3



(a) **(b)**

Fig. 5. Synthesis and EM simulations of the S-Parameters responses.

the passbands obtained in simulations of the non-uniform Q filter designed, with the same filter in coaxial SIW but with an uniform Q distribution of 270. As can be appreciated is achieved a notorious improvement in flatness applying the proposed resistorless lossy implementation.

IV. EXPERIMENTAL VALIDATION

In order to demonstrate the proposed approach, the designed filter has been manufactured. The fabricated prototype is shown in Fig. 6 and its measured results and EM simulations in Fig. 7. The final dimensions are 2.3 x 2.3 cm^2. The measured 3 dB bandwidth has a small variation of about 40 MHz compared to the simulated one, while the measured and simulated frequency rejections are in a good agreement. The measured insertion loss value at f_0 is 3.25 dB, which is slightly higher than the 3 dB obtained in simulation. The flatness is considerably improved from a coaxial SIW filter with uniform Q resonators, but with a slight variation from the simulated values, reaching 1 dBpp in the passband, instead of 0.8 dBpp. With these results the flatness obtained is equivalent to a uniform Q-filter with a Q value of 600.

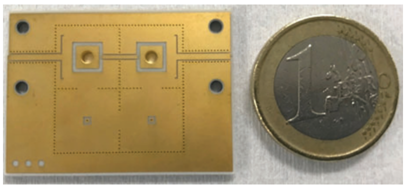


Fig. 6. Photograph of the fabricated prototype filter.

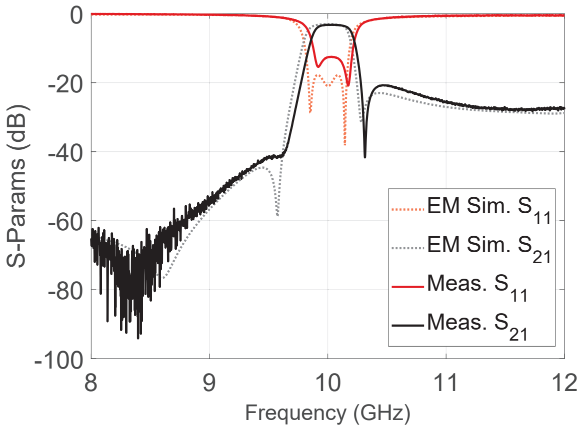


Fig. 7. Measurements versus EM simulations of the fabricated prototype filter.

V. CONCLUSIONS

In this paper, the design of a bandpass fitler with very flat response using non-uniform Q resonators is presented and demonstrated. The structure is based on the ability to control the unloaded Q-factor of coaxial SIW resonators within a very wide range, and without the need of using different technologies or introducing resistors. The obtained results show that this approach could be of promising application for filters with very demanding responses while keeping low-cost manufacturing, high integrability and very compact size.

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