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Compact Folded Bandpass Filter in Empty Substrate Integrated Coaxial Line at *S*-Band

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***Abstract*— This letter presents a novel compact folded bandpass filter in empty substrate integrated coaxial line (ESICL) technology. To obtain these compact filters, the inverters are modified to provide a 180° bend when inserted in an ESICL. As a result, the proposed filter has a more compact topology based on parallel resonators. A sixth-order Chebyshev bandpass filter operating at 3 GHz has been designed, manufactured, and measured to experimentally validate this new folded configuration. The length of the novel compact filter has been reduced by 82.2% with respect to an equivalent in-line filter, obtaining very similar results in terms of electrical response.**

***Index Terms*— Bandpass filter, empty substrate integrated coaxial line (ESICL), folded filter.**

I. INTRODUCTION

CURRENTLY, there is a great interest in the integration of traditional 3-D waveguides in planar substrates. This is due to the high quality factor, easy manufacturing, and low cost of such devices since they are made of printed circuit boards (PCBs). One of the first planar structures integrated into a PCB was the substrate integrated waveguide (SIW), which behaves like a rectangular waveguide filled with a homogeneous dielectric. Therefore, in this waveguide, the wave propagates through the dielectric, so at high frequencies, its performance is drastically reduced. In order to overcome this limitation, in the past years, different approaches have been developed to enhance the integration of traditional waveguides in PCBs. These new integration schemes have in common that the propagation through the dielectric substrate is avoided. As a result, electromagnetic waves propagate through air so that losses are notably reduced. Some examples of these structures are empty SIW [1] and air-filled SIW [2], which are rectangular waveguides, and empty substrate integrated coaxial line (ESICL) [3], an integrated and empty rectangular coaxial line.

One of the most widely employed components for microwave communications is bandpass filters. These new integrated empty waveguides, like ESICL, can provide filters with high performance, but on the other hand, they present a drawback, i.e., filters designed using empty substrate technologies present large lengths. Therefore, in these new technologies, size reduction is becoming an urgent need. This is the case, for example, of space communications: one of the most interesting possible applications of these empty SIW technologies, where there is a growing concern on reducing the size and mass of the passive components integrated into satellite payloads. In the case of filters, the desired reduction is often achieved by bending the filters, as it is done with SIW technology in [4] or with coaxial technology in [5], bending the resonators.

Therefore, in this letter, a folded filter based on ESICL technology, which is deeply analyzed in [3], is presented for the first time. The main advantages of ESICLs stem from the propagation through air. Consequently, low loss and high quality factors can be achieved. For instance, an attenuation constant of 0.9 dB/m has been obtained at 15 GHz (see [3]). In order to achieve the compact folded configuration, a new inverter topology has been developed. The inverter, besides coupling consecutive resonators, incorporates a 180° bend, which allows to obtain parallel resonators instead of a typical in-line configuration. Hence, a high degree of compactness is finally achieved.

II. FILTER DESIGN PROCESS

The proposed filter is based on the well-known in-line coupling routing scheme based on cascading serial resonators and impedance inverters. The theoretical value for the length of the resonators ($\lambda/2$) and for the inverter constants K_i is obtained as in [6]. For the considered filter (sixth-order Chebyshev response with 0.0457-dB ripple and 2% relative bandwidth), the inverter constants are $K_{01} = K_{67} = 0.1769$, $K_{12} = K_{56} = 0.0264$, $K_{23} = K_{45} = 0.0192$, and $K_{34} = 0.0183$).

The first and last inverters have to be designed as simple inverters, see inverters 1 and 7 in Fig. 1 [dimensions in Fig. 1(b)]. Since the coupling in this first inverter is

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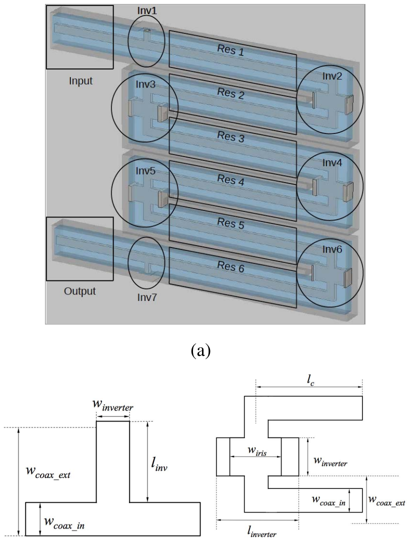

(a)

(b) (c)

Fig. 1. Inverters dimensions. (a) Filter structure. (b) Lineal inverter. (c) Folded inverter. Dimensions of the folded filter (mm): $w_{\text{coax\_in}} = 1.9173$, $w_{\text{coax\_ext}} = 6.000$, $l_{\text{inv1}} = 2.3183$, $w_{\text{iris2}} = 7.2581$, $w_{\text{iris3}} = 6.4075$, $w_{\text{iris4}} = 6.3015$, $l_1 = 43.7447$, $l_2 = 44.1015$, $l_3 = 44.2686$, $w_{\text{inverter}} = 3.5000$, and $l_{\text{inverter}} = 8.0000$.

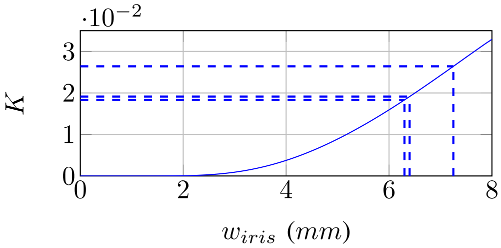

Fig. 2. Design curve for the coupling constant *K*. The dashed line shows the values used for the present filter design.

usually quite strong, the simpler inverter in [6] can be used. This inverter can be achieved using only the central layer of the ESICL so that it is easy to be fabricated. The physical dimensions and length correction for this filter can be obtained following [6].

To design the folded inverter, which is based on the geometry presented in [7], all the internal layers (3 of 5) that form an ESICL are used (see [3]). In order to achieve a higher degree of compactness than in [7], inverters are folded to provide a mean to align the filter resonators side by side (see Fig. 1). As it can be seen in this figure, there are three dimensions that control the geometry of the novel inverter: w_{inverter}, w_{iris}, and l_{inverter}. The most useful parameter to control the coupling is w_{iris}; therefore, the two others are fixed values. Their values are chosen so that extremely narrow gaps are avoided and the filter can be easily fabricated, and they are also chosen to ensure a good mechanical stability of the manufactured device, and that the maximum coupling constant of the filter $K_{\max}$ can be achieved.

Therefore, to synthesize a specific inverter constant, K_i, the appropriate value of w_{iris} must be found. Since the inversion constant only depends on a single variable, a sweep analysis has been carried out varying w_{iris}. With the results of this parametric analysis, the inversion coefficient K has been calculated from S_{11} at 3 GHz applying: $K = ((1 - |s_{11}|/1 + |s_{11}|))^{1/2}$. Fig. 2 shows the evolution of K versus w_{iris}. From this curve, the necessary w_{iris} values for the different K_i can be found.

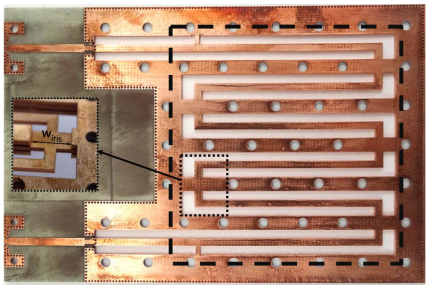

Fig. 3. Top view of the central layer of the folded compact filter. The filter is framed by a dark black dashed line. 3-D view of the irises has been marked.

Finally, the value of the length of each resonator has to be modified to correct the phase shift of the reflection coefficient, which is not exactly equal to π radians (ideal value). Therefore, each inverter is connected to input and output feeding lines with lengths approximately equal to $\lambda/4$. With these feeding lines, the reflection coefficient of the inverter should exhibit a null phase. Since these inverters are not ideal, the phase will not be zero. Therefore, the length of the feeding lines must be corrected to provide the required null phase. Since ESICL is an empty coaxial line, finding this length correction, $l_{c,i}$ for the ith inverter, is quite straightforward. For a given resonator, the correction of both inverters at its ends must be applied, and then, for the ith resonator: $l_i = \lambda/2 + l_{c,i} + l_{c,i+1}$.

III. SIXTH-ORDER CHEVYSHEV BANDPASS FILTER

Following the design process described in Section II, a sixth-order Chebyshev bandpass filter with a bandwidth of 60 MHz, minimum return loss in the passband of 20 dB, and central frequency at 3 GHz has been designed. To demonstrate its correct operation, this new filter is compared with an equivalent filter implemented with the compact in-line inverter in [7]. The dimensions of the resonators and impedance inverters of the folded filter are shown in Fig. 1. $w_{\text{coax\_in}}$ and $w_{\text{coax\_ext}}$ have been chosen to provide a characteristic impedance of 50 Ω to the ESICL, given that the height of the inner and outer conductors of the integrated coaxial are 0.866 and 2.598 mm, respectively.

The length of the compact linear filter is 293.89 mm, while the area occupied by the folded compact filter is 52.27×53.95 mm^2. There has been a reduction in the filter length of 82.2%. Of course, the folded filter will exhibit a wider footprint, but the achieved length reduction (293.89 to 52.27 mm) is of great relevance since a filter with a length of almost 30 cm, which is the case of the in-line filter based on [7], is, virtually in most of the cases, impossible to integrate. Simulations show almost identical results for both filters (comparison not shown here due to lack of space) with an insertion loss of 2.95 dB for the folded filter and 3.05 dB for the filter with a typical in-line configuration. In this way, the new folded inverter presented in this letter is validated.

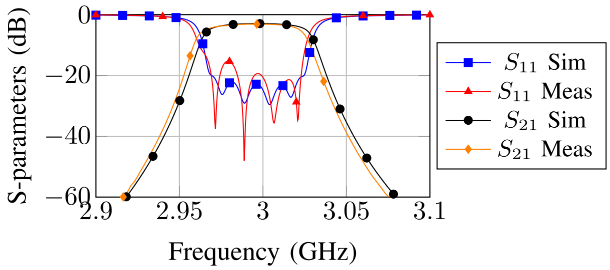

Fig. 4. Simulated and measured results for the folded compact ESICL bandpass filter at 3 GHz.

TABLE I
FILTERS COMPARISON

	Order	f_o	IL (dB)	FBW (%)	Q	Size[1] (mm)
[9]	5	7.66	1.6	7.11	253*	39.8 x 49.8
[4]	5	11	2	5.36	443*	195.6 x 163
[10]	3	5.15	5.68	3.82	152.8	67.3 x 73.8
[11]	6	4	2.5	6.25	298	35.1 x 18.9
[6]	4	15	1.59	2.93	1505	432.5 x 35
[7]	5	13	1.11	2.3	987*	254.4 x 30.3
Folded	6	3	3.14	2	593*	52.3 x 53.9

IV. EXPERIMENTAL RESULTS

The sixth-order Chebyshev folded compact bandpass filter in ESICL has been fabricated using a 4003C substrate with $\epsilon_r = 3.55$, $h = 0.813$ mm, and 26.5 μm of metallization (sum of the initial and the galvanic metallization). An LPKF Protolaser U3 milling machine has been used to manufacture the prototype. A photograph of the central layer of the folded filter and a detailed view of one of the irises is shown in Fig. 3. The large holes that appear in the images are employed to align the different layers of the filter, which are fixed by means of screws and nuts.

Two compact microstrip-to-ESICL transitions have been added to measure the filter with a vector network analyzer (see [8]). The reference planes of measurements have been shifted to the beginning of the filter using a custom ESICL thru-reflect-line (TRL) calibration kit.

There is a good agreement between measurement and simulation, as shown in Fig. 4. Insertion losses are 3.14 dB, achieving a quality factor of 593. Since this is a filter based on $\lambda/2$ resonators, there is an undesired transmission band around $2{\cdot}f_0$, $3{\cdot}f_0$, and so on.

Table I[1] gives a comparison in terms of insertion loss, fractional bandwidth, quality factor, and size of the novel ESICL folded filter presented in this letter with other compact filters implemented with similar planar technologies (SIW and multilayered substrate integrated waveguide) that can be found in the literature.

As it can be observed, the proposed configuration presents the smallest size compared with other empty configurations [6], [7], but it cannot achieve the degree of compactness provided by dielectric filled waveguides (as expected), although it is remarkable that a competitive size has been achieved.

On the other hand, since the proposed filter is based on an empty line, it provides one of the highest unloaded Q-factors, which is only below the in-line arrangements [6], [7], also implemented with ESICL. However, it would be possible to obtain higher quality factors for the proposed filter by increasing the operation bandwidth (2% in the present study). In summary, the folded filter arrangement can drastically reduce the size of the in-line filter configurations by 82.2% while maintaining a very good performance (with Q_u factor higher than other classical implementations).

V. CONCLUSION

A new folded inverter in ESICL has been presented in this letter. This inverter is applied to downsize ESICL bandpass filers. To demonstrate the good performance of these novel inverters, a sixth-order bandpass filter operating at 3 GHz has been designed, manufactured, and measured. The insertion losses obtained with the manufactured prototype are 3.14 dB and the return losses are below 15 dB in the passband, very similar to those values obtained in simulation. Using standard manufacturing equipment, it would not be possible to fabricate an equivalent compact in-line filter solution due to its associated larger size. The in-line filter without the transitions is larger than 29 cm, while the folded filter occupies an area, also without transitions, smaller than 5.5×5.5 cm^2. The total length of the filter has been reduced by 82.2%.

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[1] For easy comparison, the size column has been normalized: $\text{norm}_{\text{size}} = \text{real}_{\text{size}} \times f_0$ (GHz) / f_{norm} (GHz), where f_{norm} is the normalization frequency (3 GHz in our case). $*Q$ calculated as an estimate of a Chebyshev filter with the same characteristics as in [6].