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A High-Q Miniaturized Suspended Stripline Resonator for Pseudoelliptic Filter Design

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ABSTRACT A miniaturized suspended stripline (SSL) resonator with high unloaded quality factor is proposed in this paper. The novel resonator consists of a thin substrate with double-layer strips on both sides connected by a metallic via hole, which is suspended in the middle of an air-filled cavity and a pair of cuboid metal bricks located at the open end of the strips with a gap to realize capacitive loading. Based on a theoretical analysis of the equivalent circuit and the electric field distribution, the proposed resonator has been found possessing much higher unloaded quality factor and more compact size than the conventional SSL resonators. A compact pseudoelliptic filter centered at 670 MHz with a bandwidth of 160 MHz and a low insertion loss of approximately 0.38 dB is designed, fabricated, and measured. Two transmission zeros generated by cross coupling mechanism are located near the passband to enhance the frequency selectivity. The measured results show excellent agreement with the synthesized and simulated ones.

INDEX TERMS Miniaturized suspended stripline resonator, high unloaded quality factor, pseudoelliptic filter.

I. INTRODUCTION

Over the past decades, much attention has been drawn to suspended stripline (SSL) structure since it has been proven to be an excellent transmission-line medium for the realization of numerous types of filters [1]. Since fewer electric fields distribute inside the substrate and the majority of the electromagnetic field is shielded in the air-filled cavity, it leads to lower dielectric losses and radiation losses. The analysis method of the generalized SSL transmission-line has been presented in [2].

Generally, most of the SSL filters up to now are realized on both sides of the substrate or even multi-substrate arrangements. The design of planar microwave components using multilayer SSL structures was first proposed in [3]. For miniaturization, a general approach for the realization of quasi-lumped filters and diplexers based on the conventional SSL resonator has been presented in [4]. Furthermore, in order to significantly reduce the size of the SSL resonator, a cuboid shape brick is inserted in the open end of the resonator to realize capacitive loading [5]. In our previous work [6], a double-layer SSL resonator with high unloaded quality factor (Q_u) for base-station diplexer application was presented. However, the area occupied by the resonator is very large although it obtained a high Q_u, and the theoretical analysis of the SSL resonator is lacked. In [7]–[9], the microwave passive components implemented by ingenious substrate integrated suspended line technology. The technology is effective in the integration of planar circuits using a multilayered circuit fabrication process and has the advantages of self-packaging, lightweight and low cost. However, these structures suffer from low quality factor or low power handling capability.

In this paper, a novel suspended stripline resonator characterized by improved unloaded quality factor and more compact size is proposed. Through a detailed theoretical analysis of the SSL resonator based on the equivalent circuit method, an effective solution can be obtained with enhanced unloaded quality factor and miniaturized SSL resonators, simultaneously. An example of pseudo-elliptic filter formed by cascading five resonators with inductive cross coupling is synthetically analyzed, fabricated and measured for the experimental validation.

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II. ANALYSIS OF RESONATOR AND QUALITY FACTOR

Fig. 1(a) shows the structure of the proposed SSL resonator which consists of a suspended substrate with double-layer strip lines connected by a metallic via hole at the open end, and a pair of metallic cuboid bricks located close to the strip lines with a gap to provide capacitive loading to miniaturize the resonator.

The equivalent circuit of this SSL resonator is shown in Fig. 1(b), where the inductance L and the resistance R_c of conductor loss are due to current flows along the metallic strip as shown in the Fig. 1(c). The capacitance C_1 and C_2 respectively represent the capacitive loading between metallization and upper/lower metallic cuboid brick as shown in Fig. 1(d), and the shunt conductance $G_d(1/R_d)$ represents the dielectric loss in the substrate. Observed from Fig. 1(d), compared with the single-layer resonator form, apparently, fewer electric fields distribute in the substrate of the proposed double-layer SSL resonator. Therefore, intuitively, lower dielectric loss could lead to a much higher Q_u. To some extent, the numerical characterization of the unloaded quality factor of the proposed SSL resonator can be constructed on the basis of equivalent circuit method.

The input admittance of the equivalent circuit of the resonator shown in Fig. 1(b) is

$$Y_{in} = \frac{1}{R_d} + \frac{1}{j\omega L + R_c} + j\omega(C_1 + C_2) \tag{1}$$

And it can be simplified to a parallel RLC circuit, where

$$\frac{1}{R_e} = \frac{1}{R_d} + \frac{1}{R_c + \omega^2 L^2/R_c} \tag{2a}$$

$$L_e = L + \frac{R_c^2}{\omega^2 L} \tag{2b}$$

$$C_e = C_1 + C_2 \tag{2c}$$

R_e, L_e, and C_e respectively represent the equivalent resistance, inductance, and capacitance.

The Q_u of the simplified parallel resonant circuit [10] at ω_0 can be expressed as

$$Q_u = \omega_0 R_e C_e \tag{3}$$

$$R_e = R_d // (R_c + \omega_0^2 L^2 \big/ R_c) \tag{4}$$

Equation (4) can be deduced from equation (2a).

From equations (3) and (4), Q_u is associated with R_d, R_c, L and C_e. The proposed resonator with double-layer configuration could minimize the distribution of electric field in the substrate that means the minimum shunt conductance $G_d(1/R_d)$, and the effect of R_d contributing to R_e could be ignored. Equations (2b) and (4) could be simplified to $L_e \approx L$ and $R_e \approx \omega_0^2 L^2 \big/ R_c$ (on account of R_c is small and $R_c \ll \omega_0^2 L^2 \big/ R_c$ as R_c is low frequency conductor resistance and $\omega_0^2 L^2 \big/ R_c$ is high frequency conductor resistance). On account of $\omega_0 = 1\big/\sqrt{LC_e}$, equation (3) can be simplified to $Q_u \approx \sqrt{L_e/C_e}/R_c$.

Increasing L_e (narrowing the strip width or increasing the length of the inductive strip [5]) to enhance the Q_u results in larger R_c, and increasing C_e leads to lower frquency f_0 for miniaturization while Q_u will be decreased, this near linear relationship could be observed from the variation curves of Q_u and f_0 versus the gap between brick and substrate as

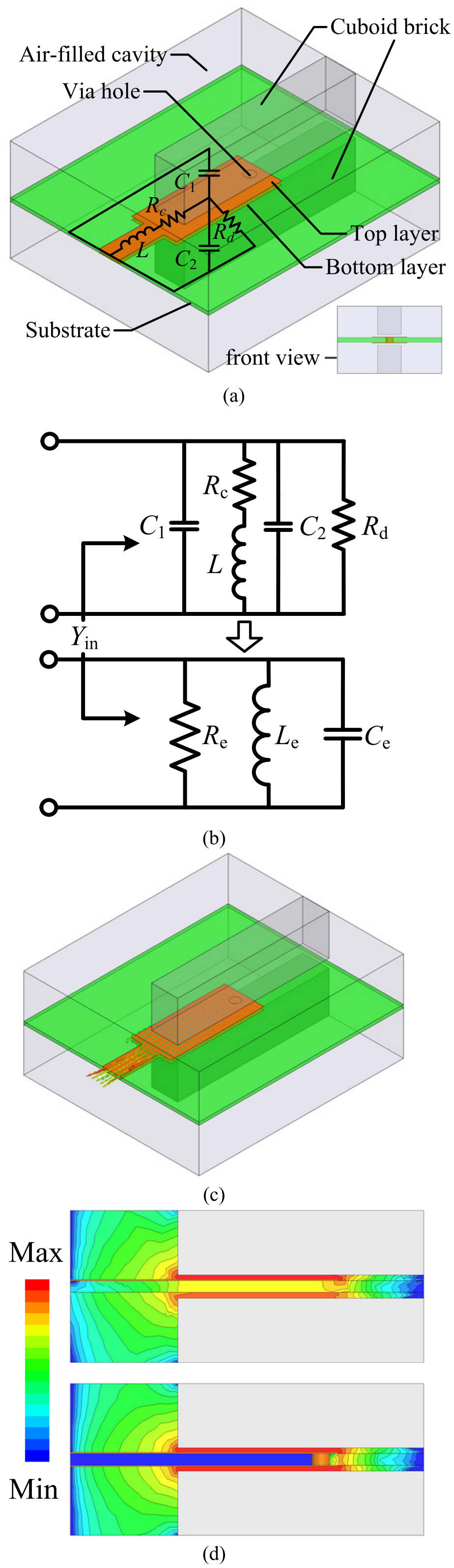

FIGURE 1. The configuration of the proposed miniaturized SSL resonator. (a) 3D view, (b) equivalent circuit, (c) side view of current distributions, (d) right side view and electric field distributions (upper: single-layer SSL resonator with bricks, lower: double-layer SSL resonator with bricks).

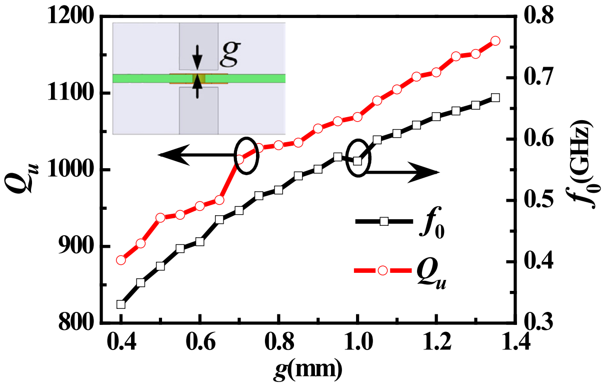

FIGURE 2. Variation curves of Q_u and f_0 versus g (gap between brick and substrate).

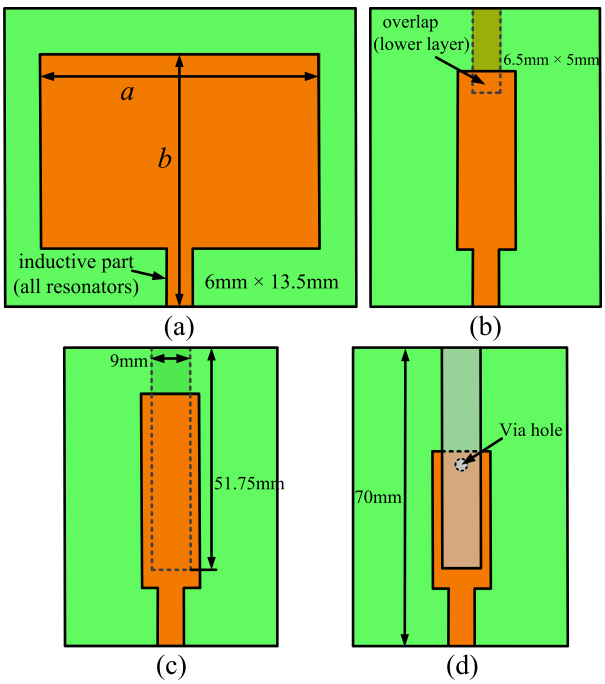

FIGURE 3. Top view of different SSL resonators. (a) Conventional SSL stepped impedance resonator, (b) single-layer SSL resonator with lower overlapping layer, (c) single-layer SSL resonator with only lower cuboid brick, and (d) proposed double-layer SSL resonator with upper and lower cuboid bricks.

plotted in Fig. 2. Consequently, a trade-off between Q_u and occupied area of the resonator is necessary.

Fig. 3 depicts the top view of four different types of SSL resonators, each form constructs with a width of 70 mm cavity and a height of 15 mm air filled above and below the substrate (Arlon AD350A, substrate thickness of 1 mm, dielectric constant of 3.5), and the dotted line areas represent the objects below the substrate. The inductive part of all resonators with the same dimensions is shorted with the inner side wall of the metal cavity. The cuboid metal bricks in Fig. 3(c) and (d) with the same air gap of 1mm are fixed at the top or bottom side of the metal cavity.

The comparison of these four SSL resonators in terms of size and unloaded quality factor is shown in Table 1.

TABLE 1. Comparison of different SSL resonators.

		Dimensions		Unloaded quality factor
	Ref. No	*a×b (mm)*	*fractions of λ(474mm)*	
(a)	[4]	65.5×59	0.138×0.124	705
(b)	[5]	13.5×55.5	0.028×0.117	350
(c)	[5]	13.5×59	0.028×0.124	650
(d)	This work	13.5×45.5	0.028×0.096	1075

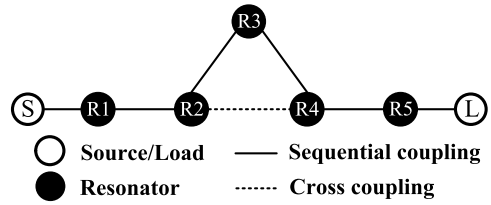

FIGURE 4. Coupling topology of the fifth-order pseudoelliptic filter.

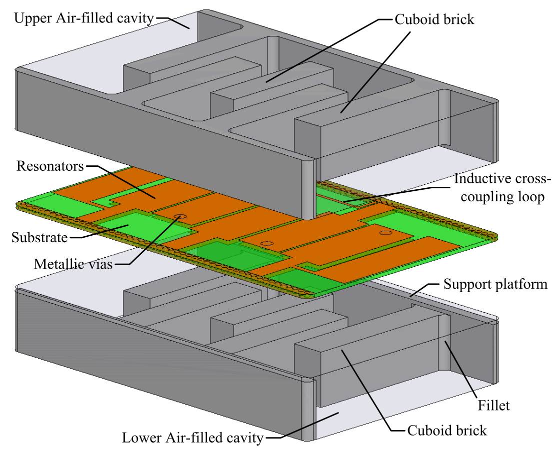

FIGURE 5. Assembly drawing of the proposed SSL pseudoelliptic filter.

The resonance frequency and its associated unloaded quality factor are calculated by the Eigenmode solver in ANSYS HFSS, and the same resonance frequency of 633MHz is obtained by adjusting dimensions of SSL resonators. Compared with the pervious reported typical SSL resonators in [4] and [5], the proposed resonator has the most compact size while maintains the highest unloaded quality factor.

III. FILTER THEORY AND STRUCTURE

Based on the above analysis of the resonance characteristic and unloaded quality factor of the proposed miniaturized SSL resonator, a fifth-order pseudoelliptic bandpass filter centered at 670MHz with bandwidth of 160MHz has been investigated for validation. Fig. 4 shows a multipath coupling topology of the filter, intuitively, there is a cross coupling [11] between resonator 2 and 4.

As shown in assembly drawing of the proposed SSL pseudoelliptic filter of Fig. 5, it consists of five cascaded SSL resonators with compact size by means of edge-coupling, and a metallic loop to realize inductive cross coupling, which can provide a transmission zero (TZ) at the upper stopband to improve selectivity of the passband. Every resonator consists of a thin substrate with double-layer stepped impedance resonators (SIR) on both sides connected by a metallic via hole, and a pair of metal bricks fixed at upper and lower side of SIR with an air gap of 1mm. Approximate design formulas for bandpass filters using parallel coupled stripline SIRs have been proposed in [12]. Spurious response can be controlled by the impedance ratio of the resonator.

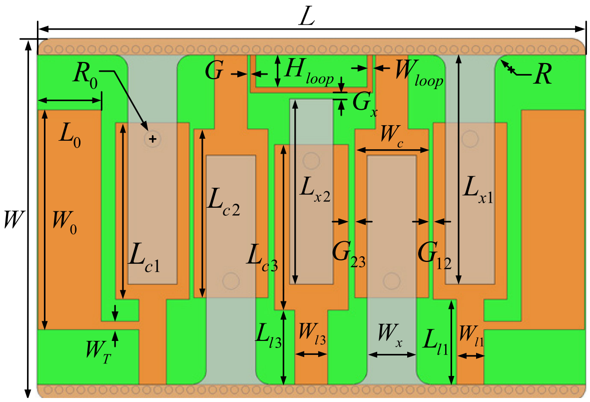

FIGURE 6. Top view of the proposed SSL pseudoelliptic filter.

An approximately symmetric normalized coupling matrix can be synthesized according to [13] and [14] as follows: $M_{12} = M_{45} = 0.8642$, $M_{23} = M_{34} = 0.6131$ and $M_{24} = 0.1698$, and the external quality factor Q_e is 4.6. The initial dimensions of each element can be precalculated, where gap between resonators can control the intercoupling, and external coupling can be adjusted by shifting the tapped feeding position. As shown in Fig. 6, the final dimensions can be optimized as: $L = 100$, $W = 66$, $L_0 = 11.5$, $W_0 = 40$, $W_T = 1.5$, $W_c = 13.5$, $L_{c1} = 32.2$, $L_{c2} = 30.8$, $L_{c3} = 30$, $W_{l1} = 5$, $L_{l1} = 15.5$, $W_{l3} = 6$, $L_{l3} = 13.5$, $W_x = 9$, $L_{x1} = 41.75$, $L_{x2} = 33.75$, $G_{12} = 0.8$, $G_{23} = 1.15$, $G_x = 1.1$, $G = 0.5$, $W_{loop} = 1$, $H_{loop} = 5.9$, $R0 = 1.5$, $R = 2$, all in mm.

IV. FABRICATION AND MEASUREMENT

The filter is manufactured on two copper (Cu) split blocks by CNC metal milling technology with whole structure machined within one block and another one as a lid to avoid misalignments. Considering the practical machining process, some corners have been filleted with a radius of 2 mm, which is also the radius of drill used. The conductive connection between carrier block and lid as described in [15] and [16] is done by rows of vias along the edges of the substrate, which is equivalent electric wall to connect the side of the mount and has already been taken into account during simulation.

Fig. 7(a) shows the photograph of the fabricated SSL pseudoelliptic filter. The planar size of the fifth-order filter is 60 mm × 71 mm (excluding the feed lines), which is equal to 0.13 λ_g × 0.158 λ_g, where λ_g is the guided wavelength at the center frequency of the filter. Simulation and measurement are accomplished by ANSYS HFSS and Anritsu MS46322A network analyzer, respectively.

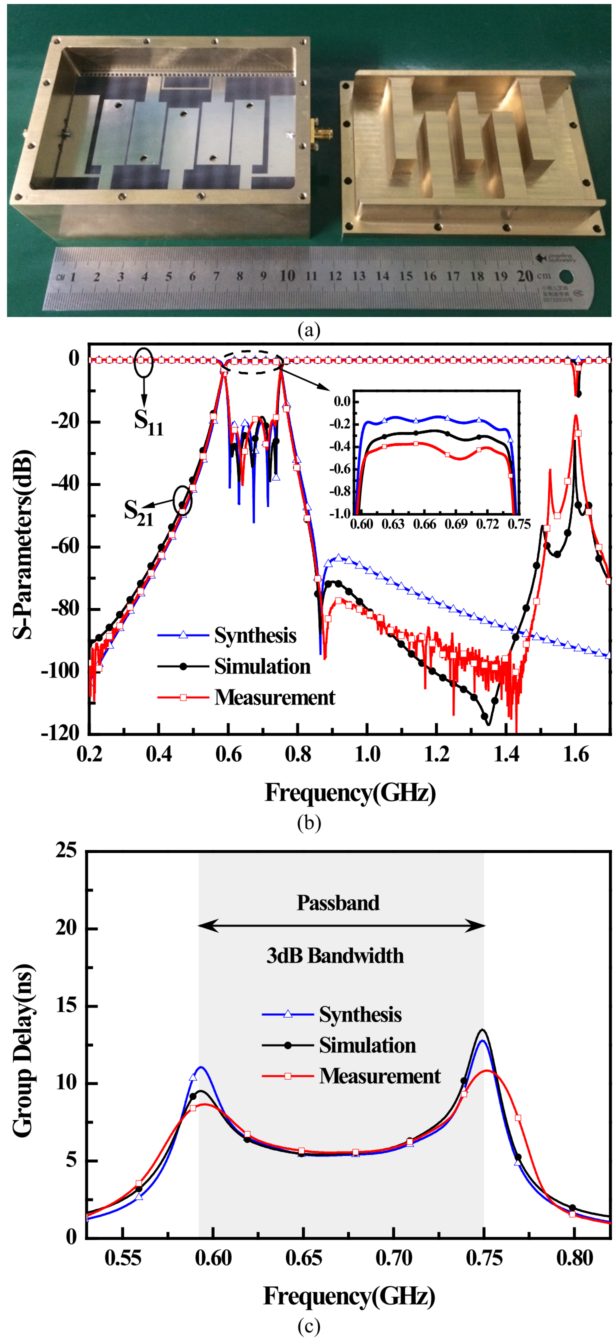

FIGURE 7. (a) Photograph of fabricated filter, (b) synthesized, simulated and measured results, and (c) passband group delays.

Fig. 7(b) shows the synthesized results of the equivalent circuit, the full-wave simulation results of the optimized geometry and the experimental results of the fabricated filter. Apparently, good agreements can be observed among them, which are centered at 670 MHz with the 3-dB fractional bandwidth of 23.8%. As expected, observed from the inset in Fig. 7(b), a closer view of the in-band insertion loss, the minimum measured insertion loss is approximately 0.38 dB, which is slightly worse and mainly attributed to input/output incomplete matching with SMA connectors.

Moreover, the return losses are all greater than 19.5 dB. The first TZ generated by the inductive cross coupling between nonadjacent resonator 2 and 4 improves the frequency selectivity. Its position can be flexibly controlled by adjusting the dimensions of the planner metallic loop. The second TZ far from the passband is due to the weak spatial inductive cross coupling between resonator 3 and 1 / 5, and a much higher rejection level of the upper stopband can be obtained.

As shown in Fig. 7(c), within the passband, the maximum variation of group delay results is less than 7 ns, which implies good linearity of the proposed bandpass filter.

V. CONCLUSION

A suspended stripline (SSL) resonator with high unloaded quality factor and compact size has been proposed in this paper. Based on the analysis of resonance characteristic and unloaded quality factor of the novel resonator, a fifth-order pseudoelliptic bandpass filter characterized by compact size and low insertion loss is designed, fabricated, and measured for validation. Good agreement has been obtained between the simulation and measurement results. This miniaturized suspended stripline filter offers a good candidate for compact, low loss and high power RF/microwave transceiver systems.

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