Compact Microstrip Low-Pass Filter Design with Ultra-Wide Reject Band using a Novel Quarter-Circle DGS Shape

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Abstract **─** A novel quarter-circle defected ground structure shape is introduced in this paper to design and implement an ultra-wide reject band low-pass filter (LPF). Moreover, an equivalent circuit model (ECM) is presented. The proposed LPF has small size and, a low insertion loss and a return loss less than -20 dB. Also, a round -20 dB suppression level ranging from 4 GHz to more than 20 GHz is achieved. The simulated results obtained by ECM and full-wave EM show good agreement with the measured ones.

Index Terms **─** Compensated microstrip line, defected ground structure (DGS), low-pass filter (LPF), quarter-circle (QC) shape.

I. INTRODUCTION

Recently, there has been an important and an increasing interest in the use of defected ground structures (DGSs) for performance improvement of microstrip filters [1-11]. A DGS unit is realized by etching off a simple shape defect from the ground plane. The structure shape can have a simple or a complicated geometry. An etched defect disturbs the shield current distribution in the ground plane. This disturbance modifies the transmission line characteristics (capacitance and inductance) and achieves slow-wave effect and band-stop property. Due to its resonant behavior, this may be compared to the simple and widely used LCR equivalent circuit model.

Usually, DGSs can offer both slow-wave (SW) propagation in the pass-band and good attenuation properties in the stop-band. Consequently, low-pass filters (LPFs) designs based on DGS with broad stop-band have been attracting researchers in latest years. Various DGS shapes for filters applications have been proposed [1-11]. Nevertheless, usually the filters' performances do not completely achieve the communication systems requirements such as compact size, ultra-wide stop-band width and low insertion loss.

In this paper, we propose a novel quarter-circle (QC) DGS shape for stop-band filter design. It shows an upper-stopband and good SW properties. A single QC-DGS generates an attenuation pole frequency which can be simply designed with structural parameters. Its equivalent circuit model (ECM) is analyzed and discussed. Furthermore, a compact ultra-wide stop-band LPF using only two QC-DGS along with compensated line is proposed. This structure type avoids employment of cascaded LPF units and allows achievement of an ultra-wide stop-band with very good insertion and return losses in the LPF pass-band. The simulation results show a good agreement to the measurement ones.

II. QC-DGS UNIT ANALYSIS AND EQUIVALENT CIRCUIT MODEL

Figure 1 shows the proposed QC-DGS pattern with its equivalent circuit model. It is composed of

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a connecting slot and two quarter-circle defected areas etched in the ground plane below a 50 Ω microstrip line. The QC-DGS unit is designed on a RO4003 substrate with a permittivity of the dielectric (ε_r) of 3.38 and a thickness (h) of 0.813 mm. The calculated width (w) of a 50 Ω microstrip line is 1.92 mm.

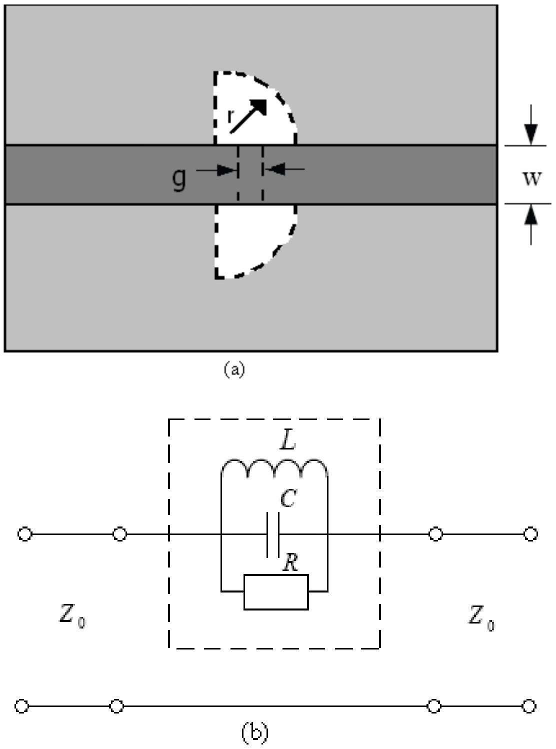


Fig. 1. The proposed of QC-DGS unit (a) geometry, and (b) equivalent circuit model (ECM).

The proposed QC-DGS pattern dimensions r and g are considered to be respectively 5 mm and 2.5 mm and the circuit elements are extracted using the following expressions [12].

$$C = \frac{\omega_0}{2Z_0(\omega_0^2 - \omega_c^2)}, \tag{1}$$

$$L = \frac{1}{\omega_0^2 C}, \tag{2}$$

$$R = \frac{2Z_0}{\sqrt{\frac{1}{|S_{11}(\omega_0)|^2} - \left(2Z_0\left(\omega_0 C - \frac{1}{\omega_0 L}\right)\right)^2 - 1}}, \tag{3}$$

where $\omega_0 (= 2\pi f_0)$ and $\omega_c (= 2\pi f_c)$ are respectively the angular resonant and 3-dB cutoff frequencies of the DGS pattern.

For the assumed ECM, the parameters C, L, and R are respectively 0.065 pF, 3.17 nH and 1.40 kΩ. The structure is investigated using the full-wave EM IE3D simulator. ECM and EM simulations results are illustrated in Fig. 2 which shows the characteristics of a one-pole LPF with a pole frequency (f0) at 11 GHz and a 3-dB cutoff frequency (fc) at 4.26 GHz. It can be observed from Fig. 2 that a broad-stop-band from 8 GHz (-10 dB) to more than 20 GHz is achieved.

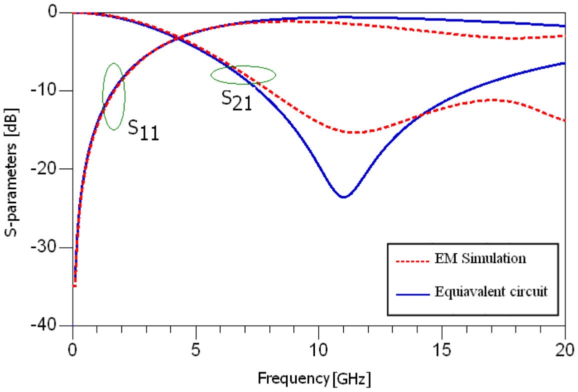


Fig. 2. Equivalent circuit model and EM-Simulations of the proposed QC-DGS pattern with r=5 mm, g=2.5 mm and w=1.92 mm.

In order to investigate the effect of the parameters r and g on the filter performances, the proposed QC-DGS unit is simulated with different r and g. First, the radius r is set successively to 3 mm, 4 mm, 5 mm, and 6 mm keeping g fixed. Next, g is set to 0.2 mm, 1 mm, 2 mm, and 2.5 mm keeping r fixed.

The simulated S-parameters are plotted in Fig. 3 and Fig. 4. It is observed that the pole frequency of the stop-band is affected significantly by both r and g. As the radius r of the proposed QC-DGS increases the pole location and cutoff frequencies move down to lower levels as shown by Fig. 3. When g increases (Fig. 4), the pole location frequency increases while the cutoff frequency remains fixed. Therefore, the proposed QC-DGS presents the significant advantage of controlling easily the pass-band and stop-band characteristics by adjusting only the parameters r and g. The pole and cutoff frequencies are plotted against r and g in Fig. 5 and Fig. 6, respectively.

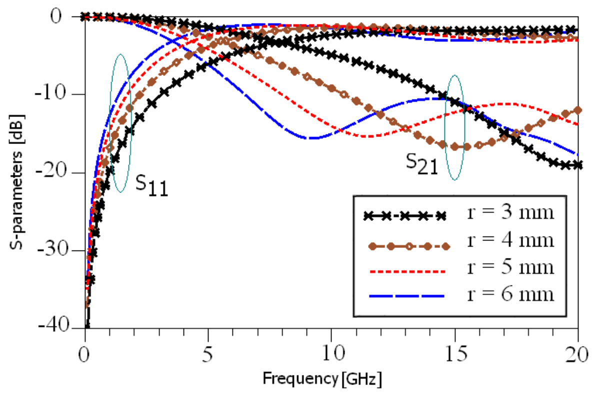


Fig. 3. S-parameters of the proposed QC-DGS cell for different r (g = 2.5 mm).

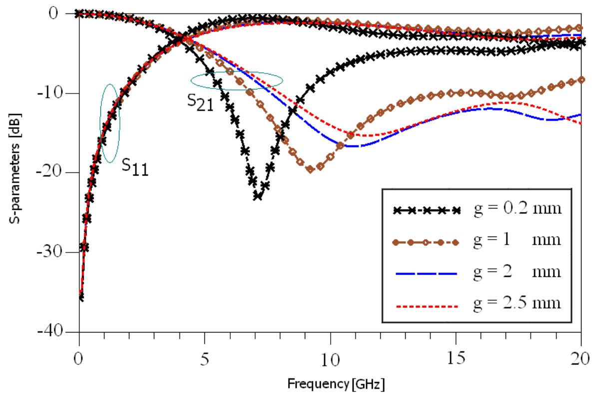


Fig. 4. S-parameters of the proposed QC-DGS cell for various g (r = 5 mm).

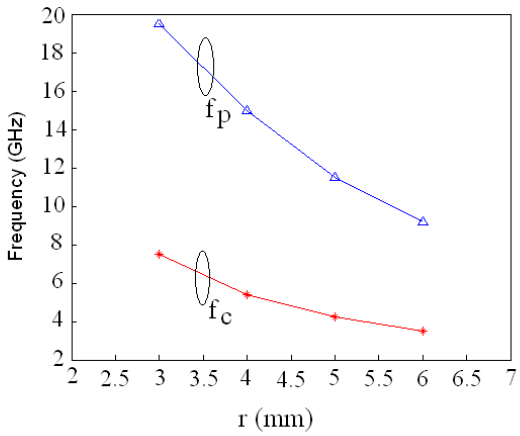


Fig. 5. Pole frequency (f_p) and cutoff frequency (f_c) versus r (g=2.5 mm).

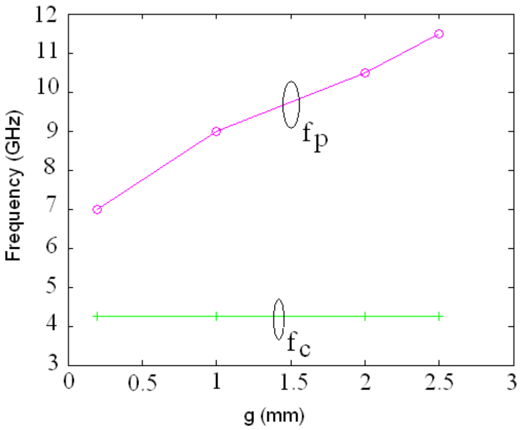


Fig. 6. Pole frequency (f_P) and cutoff frequency (f_c) versus g (r=5 mm).

In order to improve the performance of the proposed QC-DGS, a compensated 25-Ω microstrip line (w_1 = 4.93 mm) is added as shown in Fig. 7. ECM and full-wave EM simulations results are depicted in Fig. 8. It is observed that Fig. 8 shows the validity of the ECM for the proposed structure. In addition, a LPF response with upper-stopband and satisfactory SW properties is achieved.

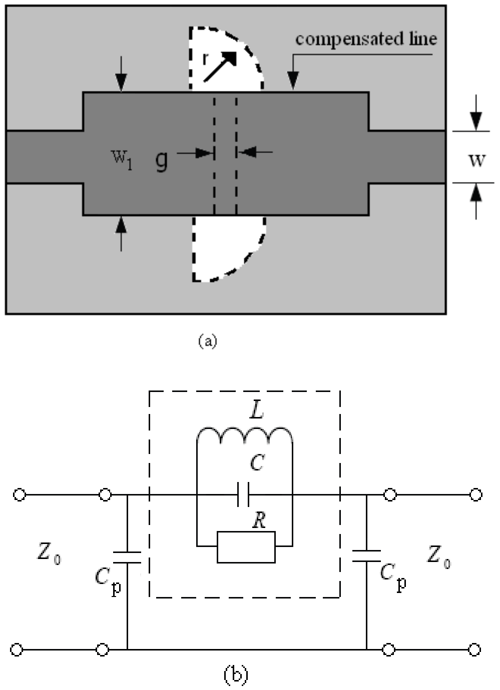


Fig. 7. Proposed of QC-DGS unit with compensated microstrip line (a) geometry and (b) equivalent circuit model (Cp= 0.562 pF).

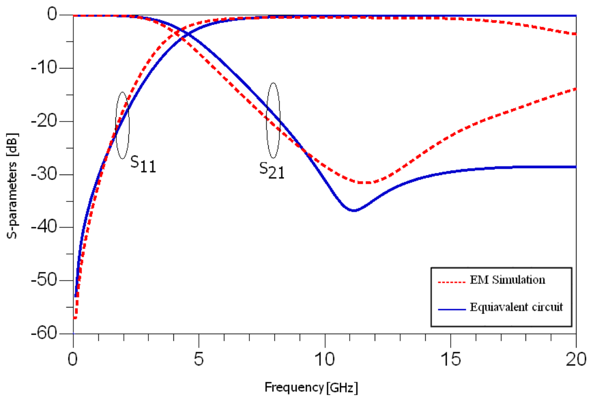


Fig. 8. Circuit and EM-simulations of the proposed QC-DGS cell with compensated line (r=5 mm, g=2.5 mm and w_1=4.93 mm).

III. FIELD DISTRIBUTION IN THE DGS-UNIT

The goal of this DGS unit investigation is to try to prove the validity of the intuitive equivalent circuit elements using the explanation of the EM-field distribution. The field simulation results are shown in Fig. 9 and Fig. 10. Figure 9 shows the field distribution in the pass-band region at the frequency of 1GHz. The magnetic field concentrates in both quarter-circle DGS heads, while a very weak electric field appears in near between both poles of this DGS structure. The transmission power between both feeds is magnetic. Both heads of this DGS will be approached to inductivity (zone I).

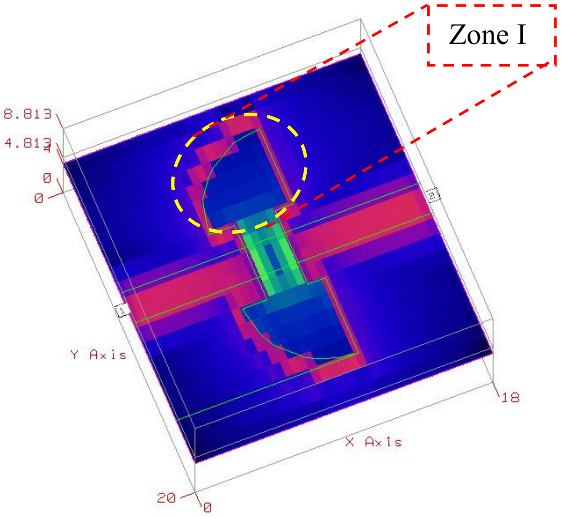


Fig. 9. Electromagnetic field distribution results in the DGS resonator at *f*=1 GHz.

Figure 10 shows a cell with a stop-band behavior at a resonant frequency of 11 GHz. The electric and magnetic fields show same distribution densities. The electric field concentrates between both heads along of the slot, which presents the capacity (Zone II). Based on this EM field investigation, the parallel LC circuit can be an approach model of the DGS unit.

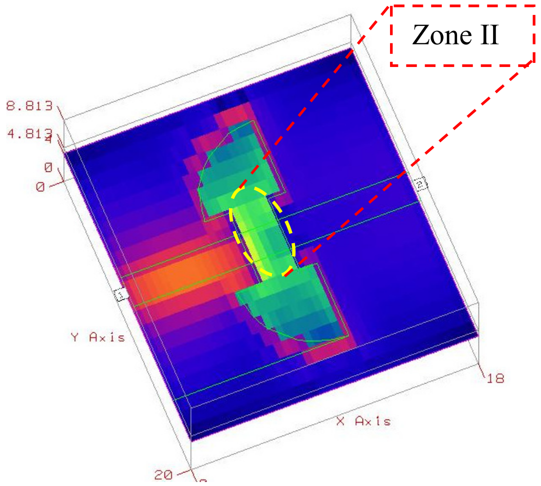


Fig. 10. Electromagnetic field distribution results in the DGS resonator at $f = f_0$ =11 GHz.

IV. ULTRA-WIDE STOP-BAND LPF DESIGN USING THE PROPOSED QC-DGS

Taking advantage from the features of the structure presented in the previous section, a compact ultra-wide stop-band LPF composed of two identical QC-DGS units and a compensated microstrip line (CML) as shown in Fig. 11(a) is designed and implemented. This structure avoids employment of LPF units and allows significant enhancement of the characteristics shown in Fig. 2 of the considered structure in the previous section. This results in an ultra-wide stop-band with good insertion and return losses in the LPF pass-band.

The separation between two adjacent resonators (d) is 6 mm, and the width of CML (w_1) is 4.93 mm. The proposed filter can be modeled as two resonators with two shunt capacitors Cp which correspond to the CML as shown in Fig. 11(b).

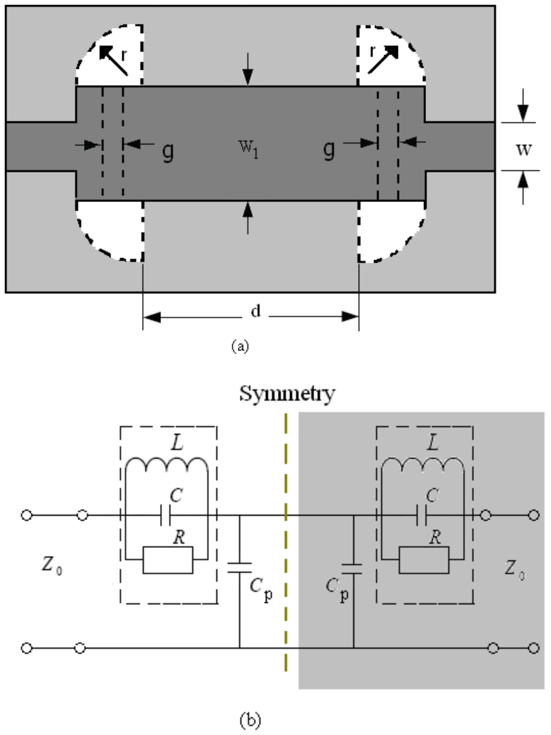


Fig. 11. The proposed ultra-wide stop-band LPF (a) geometry (r=5 mm, g=2.5 mm, w=1.92 mm, w_1=4.93 mm and d=6mm), and (b) equivalent circuit model (Cp= 0.562 pF).

The ECM and full-wave EM simulation results are shown in Fig. 12.

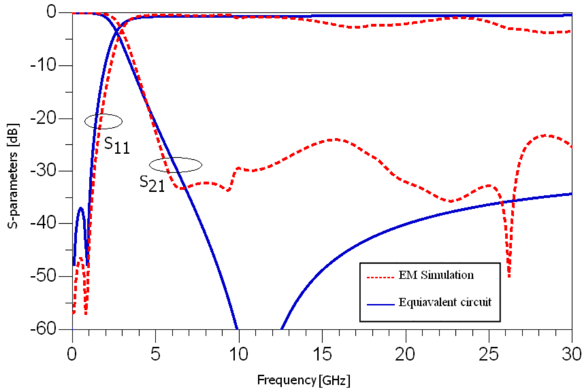


Fig. 12. Equivalent circuit model and EM-simulations of the proposed ultra-wide stop-band LPF.

From Fig. 12, it is clear that the proposed LPF behaves well in both pass-band and stop-band. It is found that the filter has a -3dB cutoff frequency at 2.95 GHz, an insertion loss of 0.1 dB which is quite small and, a return loss less than -25 dB in the whole pass-band. In addition, an ultra-wide suppression level approximately equal to -20 dB in the frequency stop-band ranging from 5 GHz to more than 30 GHz is achieved. Besides, reasonably good agreement between ECM and full-wave EM simulations can be seen except some difference appears at more than 7 GHz for insertion loss. It could be resulted from the simplicity of the lumped circuit model that the distributed effects are not included in this model. This result shows that the circuit model provides quite good performances and confirms its validity. Furthermore, it can be used as a good tool for initial design and parametric study of the structure that will be refined by EM simulation which provides more accuracy for the predicted insertion loss.

V. FIELD DISTRIBUTION IN THE LOW PASS FILTER

Figure 13 shows the EM-field distribution in the stop-band and in the pass-band of the proposed structure. The simulations of electromagnetic field are carried out using method-of-moments (MOM) by using AWR-simulator.

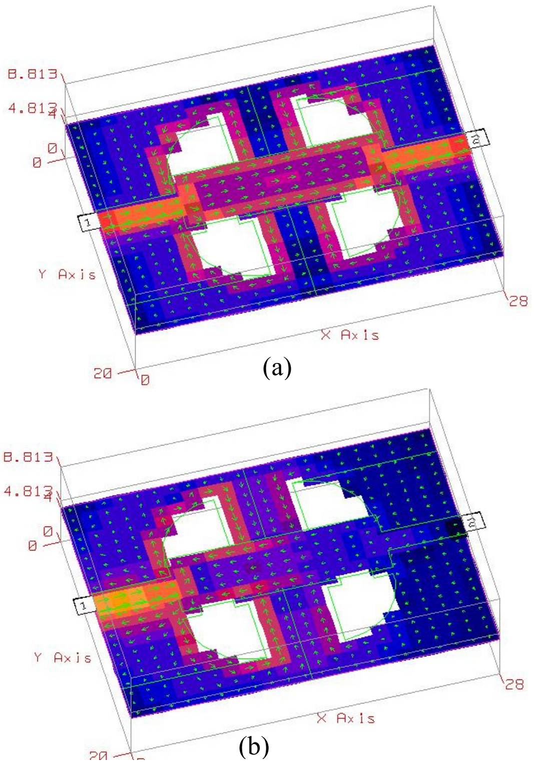
Figure 13(a) shows the distribution of E-field and H-field in the filter structure at frequency of 1.2 GHz (pass-band). At low frequency, most of the electromagnetic field is distributed around of the DGS resonators and between the input and output of the structure. At transmission domain, the magnetic coupling is the dominant; furthermore it will be easy to improve the response in the pass-band area by changing the distance between both DGS resonators. Contrariwise, from 6.2 GHz the maximal RF current concentrates in the near of the first resonator. As Fig. 13(b) shows, the compensated capacitor is short-circuited and the coupling between the DGS resonators is nearly vanishes, thus no energy flows from the input to output of the filter.

VI. IMPLEMENTATION AND MEASUREMENT

The proposed LPF with two DGSs in the metallic ground plane and a CML on the top layer with size of 24 x 15 mm^2 is fabricated as shown in Fig. 14.

Table 1: Comparison of the proposed DGS-LPF with other related LPF

	Substrate dielectric constant/ height (mm)	**Size (mm^2) x X y**	**Cutoff frequency fc (GHz)**	**Stop-band (dB) with -20 dB rejection**	**Pass-band insertion loss (dB)**	**Pass-band return loss (dB)**
Ref. [2]	4.4/0.8	21 x 20	03.5	4.3 - 15.8	< 2	-
Ref. [3]	3.38/1.524	71 x 13	02.4	3.26 - 10	< 2.26	> 5
Ref. [4]	4.4/0.8	27 x 23	03.7	3.75 - 20	< 1	-
Ref. [5]	2.2/0.788	34 x 11	1.37	4 - 12	-	> 20
This work	3.38/0.813	24 x 15	2.95	4 - 20	0.1	> 20



(a)

(b)

Fig. 13. Electromagnetic field distribution results in the LPF. (a) pass-band at 1.2 GHz and (b) stop-band at 6.2 GHz.

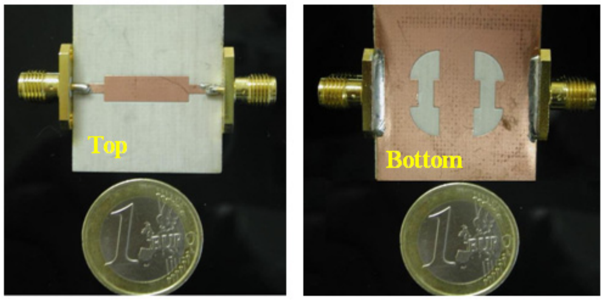


Fig. 14. Photography of the proposed ultra-wide stop-band LPF with 02 DGS patterns.

Figure 15 shows the measured and the simulated results. It is observed from Fig. 15 that the measured results agree with the simulated ones.

From the measured results (see Fig. 15), it is seen that the fabricated UW stop-band LPF has a -3dB cutoff frequency at 2.95 GHz, an insertion loss lower than 0.1 dB in the filter pass-band and, a stop-band suppression at a level lower than -20 dB from 4 GHz to more than 20 GHz. The small deviations between the simulated and measured results may most probably be caused by the usual connectors and manufacturing errors.

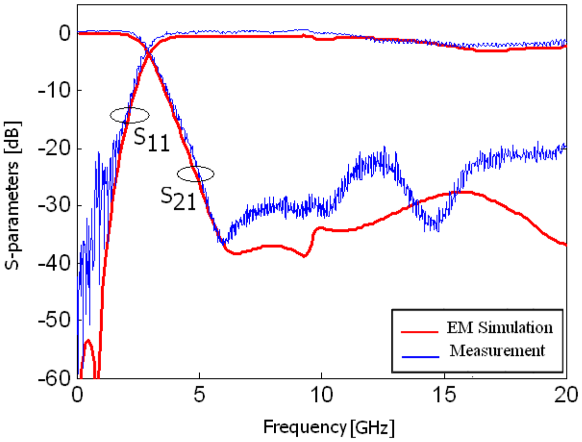


Fig. 15. Measured and simulated S-parameters of the proposed ultra-wide stop-band LPF.

The performance of the proposed DGS LPF is summarized in Table 1 with other reported LPFs for comparison. It can be seen from Table 1 that the proposed filter provides good performances in stop-band rejection and pass-band insertion loss and smaller in size (24 x 15 mm^2) than those reported in literature.

VII. CONCLUSION

In this paper, a novel quarter-circle (QC) shape defected ground structure (DGS) and its application to implement an ultra-wide reject band low-pass filter (LPF) has been introduced and investigated. The proposed LPF presents a low insertion loss of 0.1 dB, a return loss much lower than -20 dB, suppression levels approximately -20 dB from 4 GHz to more than 20 GHz and has small size. It has been shown that the simulations results achieved by circuit model and full-wave EM were in excellent agreement with the measurement ones. The proposed compact and high performance LPF can be used in a wide range of microwave and millimeter wave applications.

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