Compact Wideband Filter Element Based on Complementary Split-Ring Resonators

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ABSTRACT

A double resonance defected ground structure is proposed as a filter element. The structure involves a transmission line loaded with complementary split ring resonators embedded in a dumbbell shape defected ground structure. By using a parametric study, it is demonstrated that the two resonance frequencies can be independently tuned. Therefore the structure can be used for different applications such as dual bandstop filters and wide bandstop filters.

Keywords: Defected ground structure, Complementary split-ring resonator, Wideband filter, Dual bandstop filter

1. INTRODUCTION

It is well known that periodic structures such as photonic bandgaps (PBGs) can be added to planar transmission lines in order to obtain different types of filters.[1–4] Photonic bandgap structures, however have some drawbacks. Firstly, they consume a large layout area because usually a number of periodic patterns are required for satisfactory operation. Furthermore it is difficult to define and extract an equivalent circuit model for a PBG unit element. Equivalent circuit models allow for direct application of well known circuit design theories, such as those commonly used in the theory of RF and microwave filters. Thus the applications of such periodic structures in microwave and millimetre wave circuits are relatively limited.[5]

Recently, defected ground structures (DGSs) have attracted an increasing interest due to their simple planar structure, ease of design, and fabrication with photolitographic techniques.[1–3,6] Unlike PBGs, a unit element of defected ground structures can be easily modelled and the parameters of the circuit model can be conveniently extracted from electromagnetic simulations or measured data. Furthermore, only a few unit elements of the DGS are needed in order to achieve the same frequency response as that of a photonic bandgap structure using many unit cells. This property of the defected ground structure, which results in miniaturized circuits, makes it very popular particularly in the microwave filter design.

In brief, the simplicity of modelling, ease of fabrication and compactness have resulted in vast applications of these structures in many microwave and millimetre wave circuits such as filters, power dividers, couplers or amplifiers.[7–12] It is worth mentioning that in addition to the intrinsic compactness, a defected ground structure also adds a slow wave characteristic to the host transmission line (TL). As a result, TLs loaded with defected ground structures present smaller microwave structures and components.[3,4,12]

The split ring resonator (SRR), originally proposed by Pendry,[13] is a resonant element that is relatively small compared to the wavelength at the frequency of operation and can be excited by an external time varying magnetic field parallel to the ring axis. Due to negative effective permeability near the resonance frequency,

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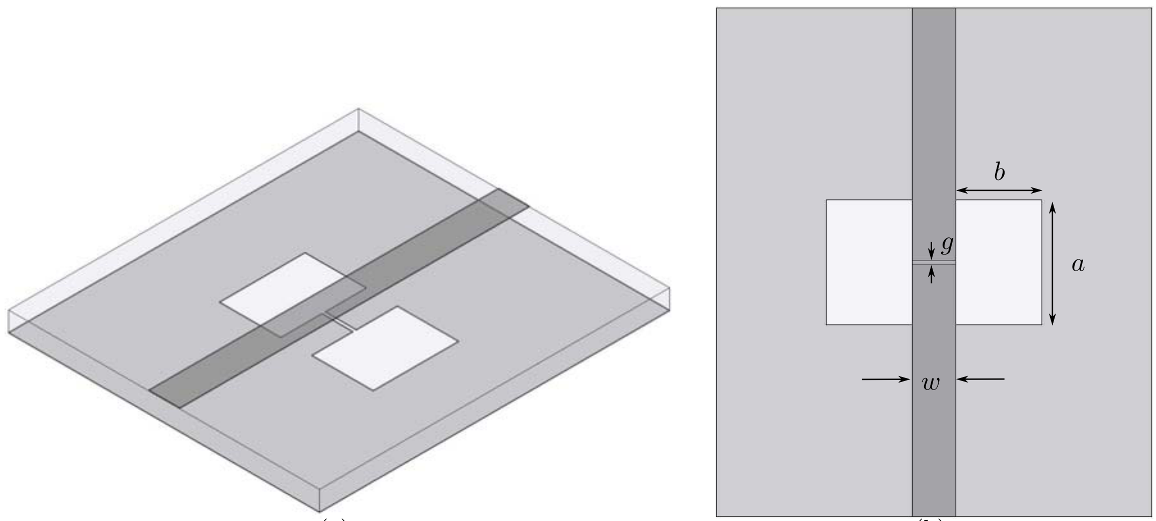

(a) (b)

Figure 1. A 3D view (a) and a top view (b) of a microstrip line loaded with a dumbbell shape defected ground structure.

an SRR element coupled to a transmission line is able to inhibit the propagation of electromagnetic wave in a narrow frequency range.[14,15] The complementary split ring resonator (CSRR) was proposed as a dual element of SRR. Similar to the SRRs, CSRRs are able to provide a rejection band around their resonance frequency.[16,17]

DGS and CSRR structures, have advantages and disadvantages. For instance, a CSRR provides a sharp transition between the stopband and passbands. However, it provides a very narrow rejection band. In contrast, in spite of providing a relatively wide stopband, DGS suffers from slow transitions between passbands and stopband. Thus, in this paper a TL loaded with a combination of DGS and CSRRs is proposed. This loaded TL provides a relatively wide rejection band with sharp transitions.

2. DGS AND CSRR SIMULATION AND MODELLING

2.1 Defected Ground Structure

Fig. 1 shows the three dimensional and top views of a microstrip line with a dumbbell-shaped defected ground. The defect structure is composed of two rectangular areas etched in the ground layer on both sides of the microstip line. The two rectangular areas are connected through a narrow slot laid beneath and across the transmission line. The TL, shown in Fig. 1(a), has a width of $w = 1.34$ mm resulting in a characteristic impedance of 50 Ω on a substrate with a relative permittivity of 10 and a thickness of 1.65 mm. All the simulations are performed using the full-wave 3D electromagnetic field simulation tool HFSS.[18] Fig. 2 depicts the simulated transmission coefficient of the structure for slot widths $g = 0.1$ mm, 0.3 mm and 0.5 mm and rectangular defect lengths $a =$ 1.6 mm, 2.2 mm and 2.8 mm. For simplicity, the rectangular defect width $b = 1.6$ mm is kept constant in all simulations. It is clear from the results that in a TL with a dumbbell shape DGS, an increase in the dimensions of the rectangular defects results in a decrease in the resonance frequency. Narrowing the slot width decreases the resonant frequency as well. These effects can be explained by the current and charge distributions in the ground layer. In fact, charges are accumulated on both sides of the slot and therefore this adds some series capacitance to the TL, while the return current route becomes longer because of the rectangular defects, which results in an increase in the inductance of the TL.[19] Therefore, a microstrip line loaded with a dumbbell shape defected ground structure can be modelled using a parallel LC resonator connected in series with the transmission line model as shown in Fig. 3(a). In this model the capacitor represents the slot while the inductor represents the rectangular defects. Thus, the resonance occurs at $\omega_0 = 1/(LC)^{1/2}$, which shows that a TL with dumbbell shape DGSs has a bandstop property. Furthermore, the figure clearly shows that the TL loaded with DGS provides a

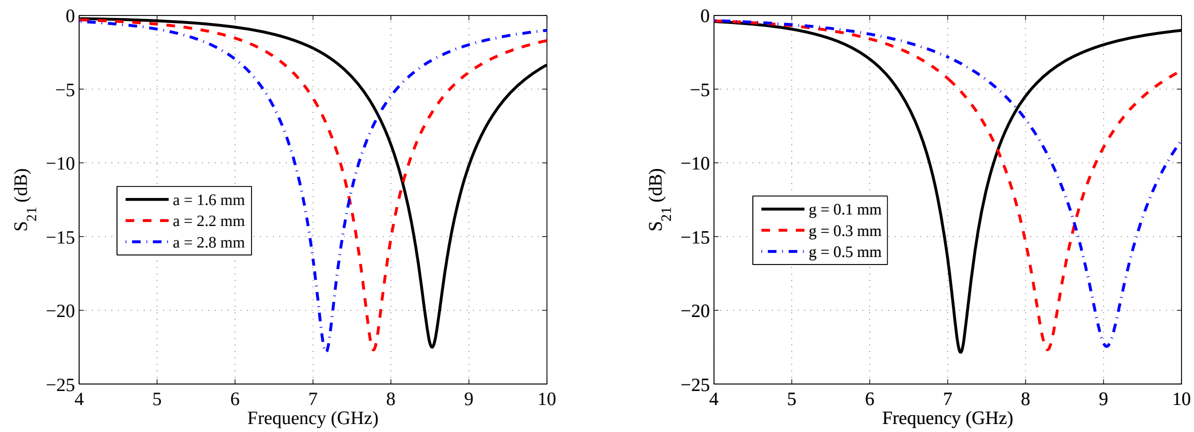

Figure 2. Variation of the resonance frequency in terms of (a) the rectangular defect width a, with $g = 0.1$ mm and (b) the slot width g, with $a = 2.8$ mm. The substrate thickness is 1.65 mm with a relative permittivity of 10 for all cases.

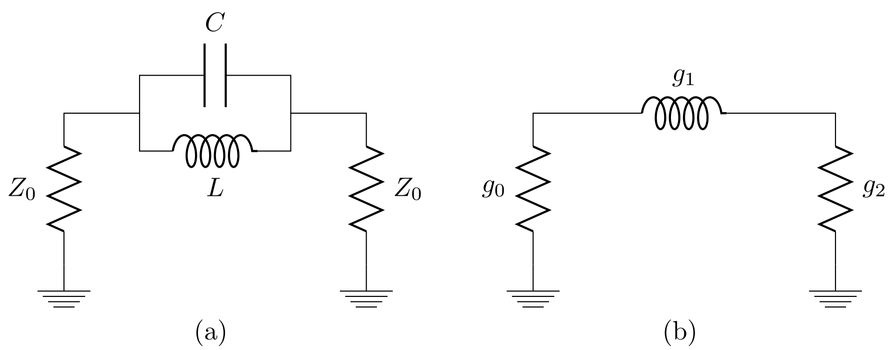

Figure 3. (a) Equivalent circuit of the microstip line with dumbbell shape defected ground, and (b) one-pole Butterworth lowpass filter prototype.

stopband with slow transitions between stopband and passbands.

Two different approaches can be exploited to extract the parameters of the equivalent circuit model, i.e., the curve fitting approach and the analytical approach. In the curve fitting approach the S-parameters of the DGS-loaded TL are simulated or measured, then an optimization technique is used to fit the S-parameters of the circuit model to the simulated or measured S-parameters. In the analytical approach, the frequency response of the DGS is compared to the response of a standard prototype filter. Based on this comparison, the values of the circuit model components are extracted through some analytical equations. Fig. 3 depicts the equivalent circuit of the DGS and the prototype of the one-pole Butterworth low-pass filter. These two circuits must have an equivalent impedance or admittance at the cutoff frequency. Also, L and C must comply with $\omega_0 = 1/\sqrt{LC}$ to have a resonance at ω_0. Thus, L and C in the equivalent circuit model can be obtained from

$$C = \frac{\omega_c}{Z_0\, g_1} \cdot \frac{1}{\omega_0^2 - \omega_c^2}, \tag{1}$$

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

where ω_c is the 3-dB cutoff frequency, $g_1(=2)$ is the element value of the one-pole Butterworth LPF prototype and $Z_0 = 50\,\Omega$ is the port impedance of the filter.

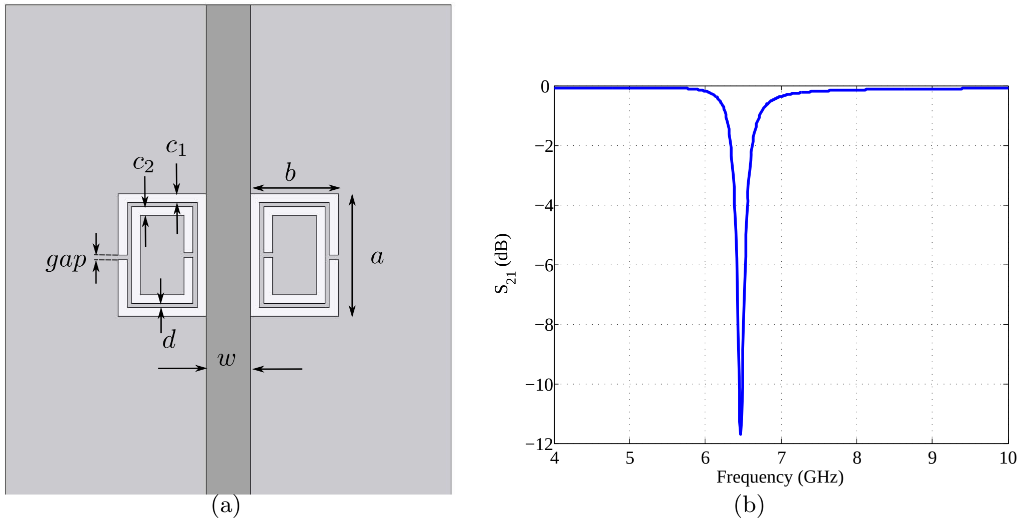

Figure 4. Microstrip line loaded with a pair of complementary split ring resonators (CSRRs), (a) the top view and (b) the simulated transmission coefficient of the structure in dB.

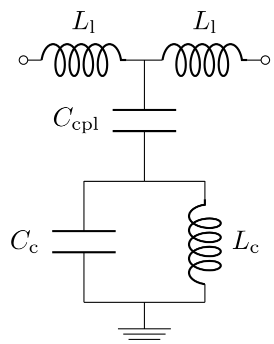

Figure 5. Equivalent circuit model of a microstrip line loaded with a pair of complementary split ring resonators (CSRRs).

2.2 Complementary Split Ring Resonators (CSRRs)

The top view of a microstrip line loaded with two complementary split ring resonators (CSRRs) etched in the ground layer is depicted in Fig. 4(a). For 3D electromagnetic simulation of the structure the substrate thickness of 1.65 mm and the relative permittivity of 10 are used. The CSRR dimensions are chosen as $a = 2.8$ mm, $b = 1.6$ mm, $c_1 = c_2 = 0.2$ mm, $d = 0.1$ mm and $gap = 0.1$ mm. The simulated transmission coefficient of the structure, depicted in Fig. 4(b), shows that a CSRR-loaded microstrip line inhibits transmission in a narrow band of frequency around the CSRRs' resonance frequency. Compared to the stopband of the microstip line loaded with a defected ground structure, the rejection band of the CSRR-loaded TL is sharper and narrower.

A unit cell of the CSRR-loaded TL can be modelled as a parallel LC resonator, which is capacitively coupled to the microstrip line as shown in Fig. 5. In this model C_{cpl} represents the electric field coupling between the CSRR and TL and the parallel LC represents the capacitance and inductance of the CSRR itself.[20] The parameters of the equivalent circuit model can be extracted using either analytical method or curve fitting method.[21] It is well known that the resonance frequency of a transmission line loaded with CSRRs can be changed by manipulating the CSRRs' physical dimensions. For instance, an increase in c_1 or c_2 results in a decrease in C_{c}, which in turn results in an increase in the resonance frequency.

Again, it is worth mentioning that this is a significant advantage of the DGS and CSRR that a single element of the structure can be modelled and all the parameters of the model can be extracted, while periodic structures such as photonic bandgaps impose difficulties in defining and modelling of the unit elements.

3. WIDEBAND FILTER ELEMENT BASED ON CSRR AND DGS

Fig. 6 shows the three dimensional and top view of a microstrip line loaded with a CSRR-DGS structure. The defected structure can be assumed either as two CSRRs connected to each other through a slot line, or two CSRRs embedded inside a dumbbell shape defected ground structure. The latter consideration gives a better intuition about the behaviour of the structure. Fig. 7 illustrates the effects of changing the dimensions of the CSRRs on the transmission S_{21} of the CSRR-DGS loaded microstiop line. The same substrate and TL dimensions as the two previous simulations are used for the simulation of the CSRR-DGS structure. For all the simulations shown in Fig. 7(b) $a = 2.8$ mm, $b = 1.6$ mm, and $g = 0.1$ mm to keep the DGS dimensions constant. Fig. 7.(a) depicts the variation of the resonance frequencies in terms of c_1, which is the outer slot width of the CSRRs as shown in Fig.6(b). This parametric study shows that although a decrease in c_1 leads to an increase in the frequency of the lower resonance it has a very small effect on the higher resonant frequency. Thus it can be deduced that one of the resonances (lower resonance in this case) is related to the CSRR, while the other resonance (higher resonance in this case) is due to the DGS. In a similar manner Figs. 7(b) and (c) show that varying c_2 and the gap size, does not have a significant effect on the frequency of the second resonance.

Therefore, from these simulations it can be deduced that the resonance related to the CSRRs can be tuned independently from the resonance of the DGS. This is one of the most important advantages of this structure compared to other dual resonance structures such as combined SRR and DGS, where there is a strong coupling between the two components.[22] This feature makes it much easier to design and realize different RF and microwave circuit components such as dual stopband filters or wide stopband filters. It is worth mentioning that since the CSRR is located inside the rectangular defect of the DGS the structure footprint is kept compact. This is another important characteristic of the proposed structure, which leads to miniaturized circuits.

4. CONCLUSION

A novel defected structure based on CSRRs and a dumbbell-shaped DGS is proposed. Since the CSRRs are located inside the square shape defection areas of the DGS the proposed structure is very compact. It is

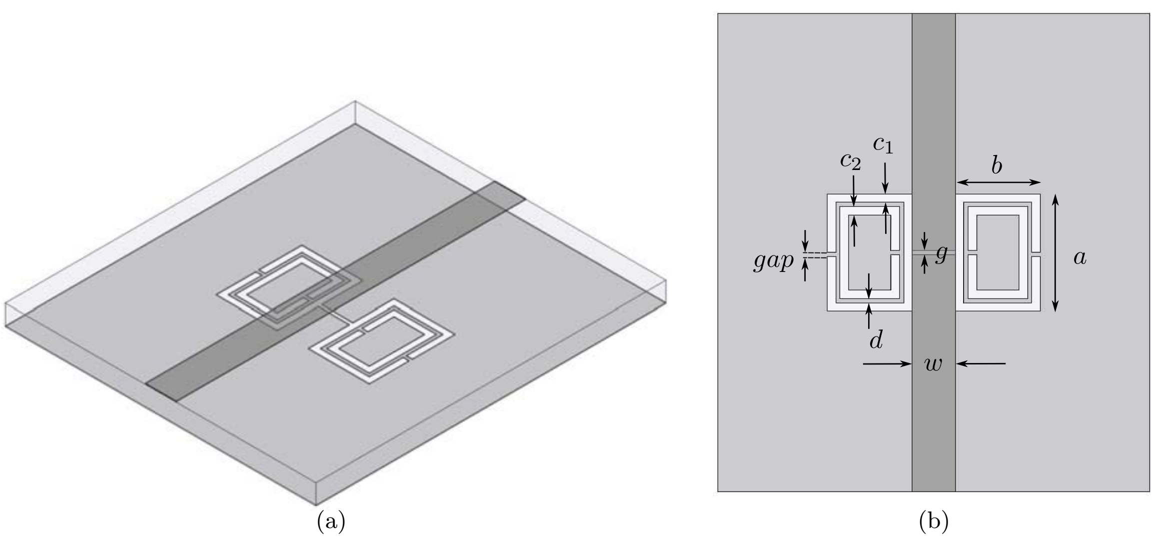

Figure 6. Three dimensional and top view of a microstrip line loaded with a CSRR-DGS. The structure can be either considered as a pair of complementary split ring resonators connected to each other through a slot or two CSRRs embedded inside the rectangular defect of a DGS.

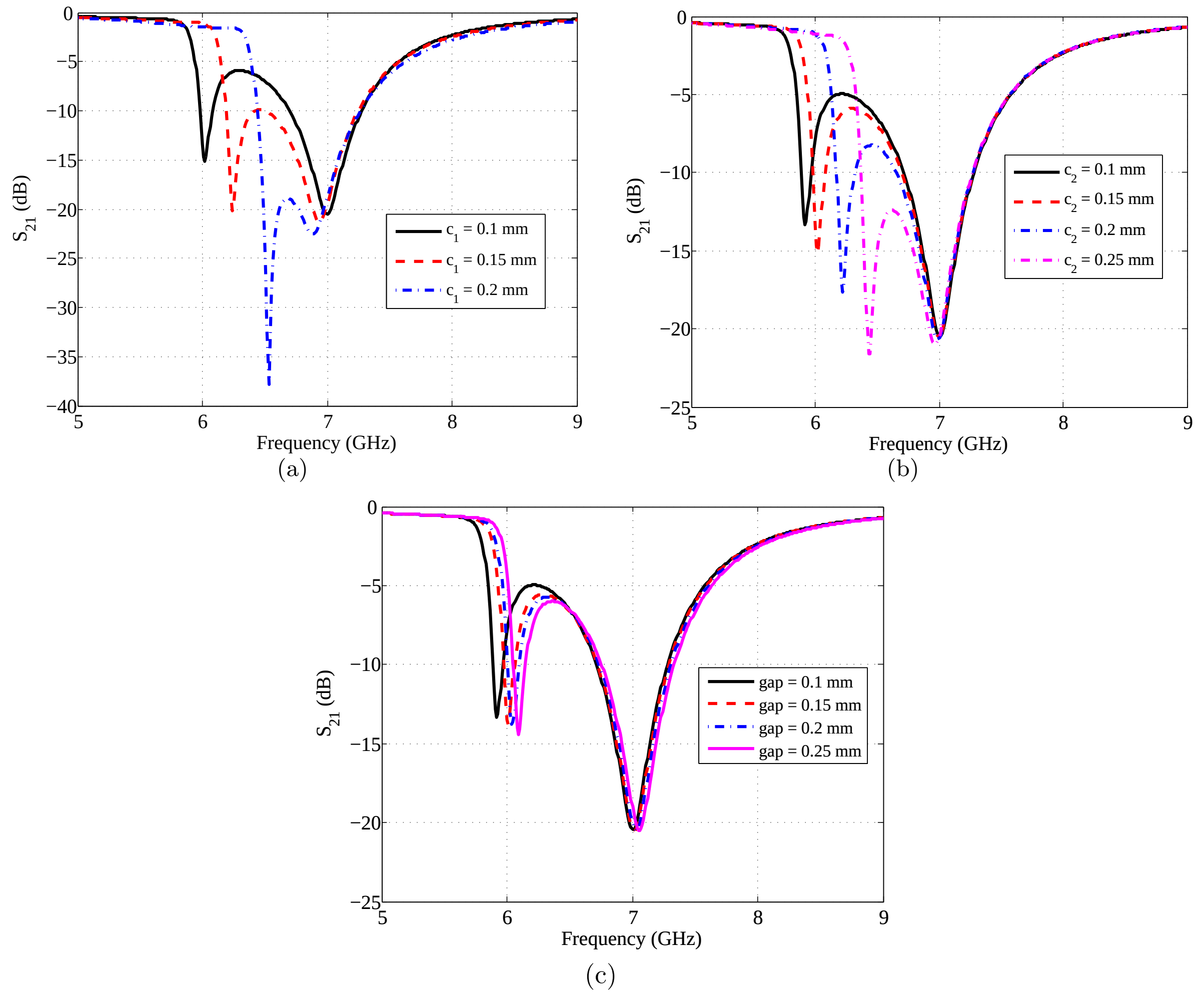

Figure 7. Simulation results for the S_{21} of a microstrip line loaded with a CSRR-DGS. The results show that any change in c_1, c_2 and gap size only changes the resonance frequency of the CSRR and does not have a significant effect on the DGS resonance frequency.

demonstrated that the structure has two resonant frequencies that can be independently adjusted by manipulating the physical dimensions of the CSRRs and DGS. Having a small layout area and two independently adjustable resonances makes the structure a useful component for compact microwave circuits such as wideband filters or double stopband filters.

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