Novel Metamaterial-Inspired Planar Cells for Compact Filtering Applications

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Abstract

In this paper, three split ring resonator based coplanar waveguide cell configurations operating in C-band are studied. Particularly, the transmission lines have been loaded with metallic shunt strips and/or series gaps. The properties of these structures can be controlled by properly designing the loading elements. For instance, the wide shunt wires permit to control the upper band rejection levels, and the addition of series capacitances to previous unit cell implementations provides a transmission response almost symmetric while exhibiting a right-handed character along the pass band, contrary to conventional left-handed lines. In addition, a relevant enhancement of the loaded Q quality factors, preserving low insertion losses, is pointed out. In a second stage, improved out-of-band rejection properties have been obtained by the use of cascaded basic cells and appropriate optimization processes. As a consequence, the proposed filters can be foreseen for practical applications relying on the tradeoff found between selectivity, insertion losses and out-of-band rejection. The interpretation of the results is based on full-wave electromagnetic analysis and measured responses of different prototypes designed for microwave operation.

Keywords: coplanar waveguide; left-handed lines; loaded lines; metamaterial; microwave filters; split-ring resonators; transmission lines.

1. Introduction

In 1968, Victor Veselago studied an hypothetical medium having simultaneously negative values of permeability and permittivity, showing that indeed an electromagnetic wave could propagate in such a medium [1]. Veselago demonstrated that if this isotropic medium existed, the wave vector k would be anti-parallel to the direction of the Poynting vector S .Consequently, while energy still travels away from the source, wavefronts travel backward towards the source. This is distinctly different from the isotropic medium with positive ε and μ, where the wave and the Poynting vectors are parallel. Veselago coined the term "left-handed substances" to refer to these materials, because of the left-handed triad formed by the E, H, k vectors. Furthermore, he showed that a left-handed substances will have negative index of refraction, negative phase advance, and the reversal of the Doppler shift and Vavilov-Cerenkov effect. This is opposed to the "right-handed substances", where the triad is right-handed, as it can be seen in Fig. 1.

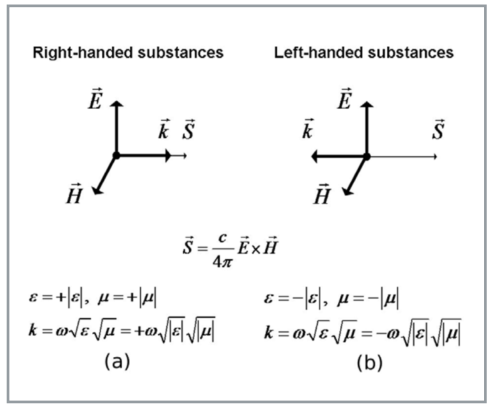


Figure 1. *Vector assignation for (a) right-handed substances and, (b) left-handed substances.*

Without a real material to demonstrate these predicted properties, Veselago's theoretical work was likely regarded as an exotic discussion for the subsequent thirty years. Nevertheless, an important advance was presented in 1996 when Pendry published a method to obtain negative permittivity at microwave frequencies [2]. Pendry used a collection of metallic rods, which behave as a plasma medium when the electric field vector is aligned to the rods. These wires are periodically assembled in a cubic lattice, as shown in Fig. 2.

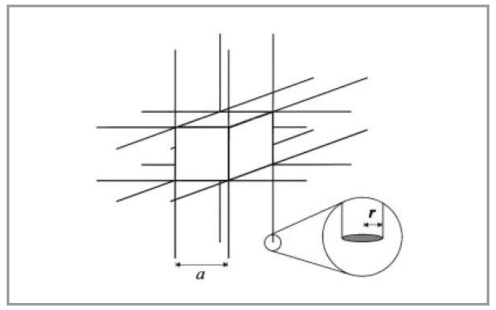


Figure 2: *Periodic structure composed of infinite conducting wires arranged in a simple cubic lattice, from [2].*

As pointed out by Pendry, the structure produces an effective dielectric function with the following form:

$$\varepsilon_{eff}(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \qquad [1]$$

$$\omega_p^2 = \frac{n_{eff}e^2}{\varepsilon_0 m_{eff}} = \frac{2\pi c_0^2}{a^2 ln(a/r)} \qquad [2]$$

In the above equations, γ is a damping term representing dissipation of the plasmon's energy into the system, ω is the angular frequency, and ω_p is the plasma frequency given by equation (2). It is worthwhile to note that in simple metals, γ is small compared to ω_p. In addition, n_{eff} is the electron effective density, e is the electron charge, m_{eff} is the electron effective mass, a is the separation between rods, and r the radius of the rods. The permittivity of the plasma is therefore essentially negative below the plasma frequency ω_p, at least down to frequencies comparable to γ. With this kind of metallic arrangement, the angular plasma frequency ω_p can be easily tailored by simply adjusting the lattice value a, and the radius of the wires r.

In 1999, Pendry followed that work with a method to achieve negative permeability [3]. He proposed various magnetic resonant structures such an array of cylinders, a capacitive array of sheets wound on cylinders, an array of swiss roll capacitors, and an array of split rings, see Fig. 3.

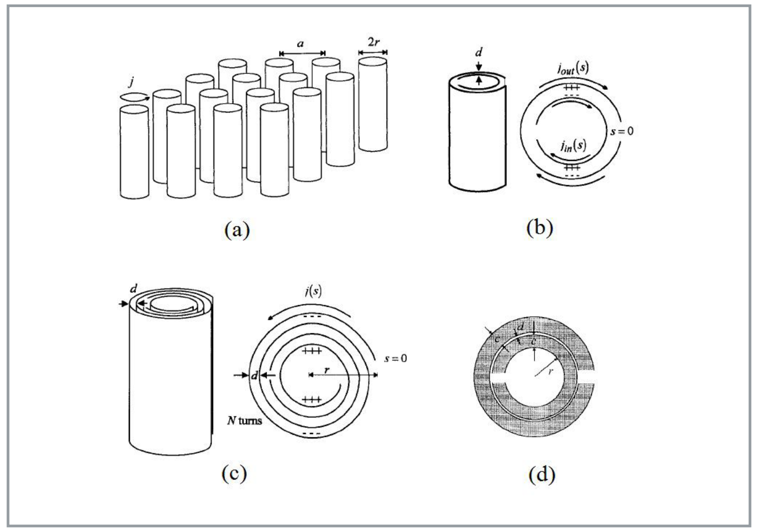


Figure 3. *Resonant microstructures which display magnetic response. Square array of (a) metallic cylinders, (b) cylinders with internal structure, (c) metallic sheets wound around each cylinder in a coil, and (d) split rings, from [3].*

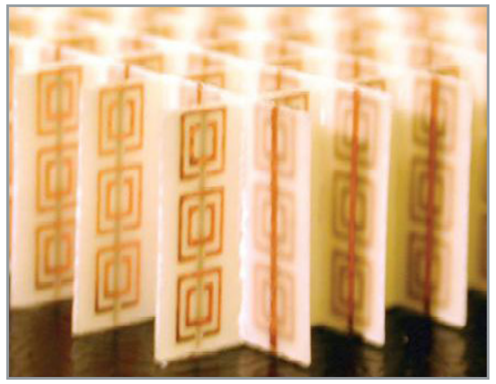
These structures produce a magnetic response when magnetic fields are applied along it's axis, but do not display magnetism in other directions. The effective permeability of the structures depicted in Fig. 3 (b), (c), and (d), can be generally defined by equation (3). In the case of the array of metallic cylinders, shown in Fig. 3 (a), only the imaginary part of the permeability varies, whereas the real part is equal to unity.

$$\mu_{eff}(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\Gamma\omega} \qquad [3]$$

In equation (3), ω is the angular frequency, F the filling factor with material that is magnetically active, ω_0 the resonant frequency, and Γ the damping of the frequency. From this equation, theory predicts a negative permeability in a small frequency range above the resonant frequency ω_0.

Left-handed substances have negative index of refraction, negative phase advance, and the reversal of the Doppler shift and Vavilov-Cerenk–ov effect

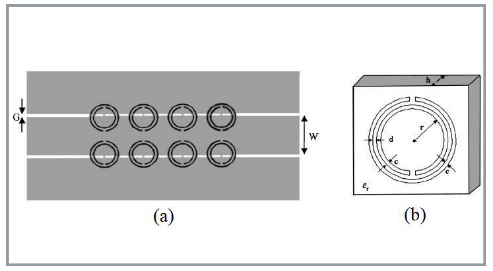
In both works, Pendry used the fact that electrically small metal inclusions could change the effective material properties [4]. Pendry's insight was that the use of a resonant structure could drastically change the properties of the material near the resonance, and negative effective values of permittivity or permeability could be achieved for the properly designed structure. No long after, Smith demonstrated the presence of both negative permittivity and permeability in a man-made (or artificial) metamaterial composed of metallic rods and split rings [5–8], see Fig. 4. In these structures, split ring resonators (SRRs) produce a negative permeability close to the resonance, while the rod structures generate a negative permittivity in an adjustable frequency range, as aforementioned.



■ **Figure 4.** *Composite medium with simultaneously negative permeability and permittivity, from [8].*

With both a methodology to achieve negative parameters ε and μ, and their experimental verification, the field of metamaterials has grown quickly, and practically every domain of electromagnetism bares re-investigation in this new light. The main research work has been concentrated on the theoretical consequences of negative parameters, as well as techniques for practically realizing left-handed media for various 2D and 3D optical/microwave concepts and applications. Among recent concepts, properties, applications, and devices based on engineered metamaterials, we can mention double-negative materials [9,10], negative-index materials [11,12], backward-wave media [13], negative-phase-velocity media [14, 15], negative angles of refraction [16, 17], sub-wavelength waveguides [18–22], Cerenkov radiation [23], enhanced focusing [24], perfect lens [25], backward wave antennas [26–28], photon tunneling [29,30], enhanced electrically small antennas [31], tunability [32–35], electromagnetic bandgap surfaces [36], reflectors [37], and cloaking [38]. These 3-D volumetric and 2-D planar DNG metamaterials have been constructed by embedding in host media various classes of small inclusions such as wires and SRRs [8, 39–46], broadside coupled SRRs [47], capacitively loaded strips and SRRs [10], omega structures [48–52], space-filling elements [53], and interdigitated series capacitors and shunt stub inductors [54], just to cite a few.

In particular, frequency selective structures composed of metamaterials, which will be deeply considered in the content of this paper, have opened the path to a new range of passive devices for guided applications. Regarding one-dimensional (1D) frequency filtering structures, such selective artificial media supporting left-handed propagation were firstly proposed by Martin et al. in 2003 [55] by magnetically coupling a shunted coplanar waveguide (CPW) and pairs of SRRs, see Fig. 5. Thereafter this first contribution, several designs have been presented [56-62] in order to improve the initial performance and broaden the range of applications.



■ **Figure 5.** *Layout of the (a) SRR based left-handed CPW structure and, (b) geometrical parameters of the SRR, from [55].*

In this implementation, the SRRs (black in the figure) are etched on the back substrate side, underneath the slots, to achieve high magnetic coupling between line (grey metal planes) and rings at resonance. The presence of the rings leads to an effective negative valued permeability in a narrow band, and by simply adding shunt metallic strips between the central strip and ground planes negative permittivity is achieved. The cited structure generates a narrow pass band above the SRR's resonance, where the double negative condition is fulfilled.

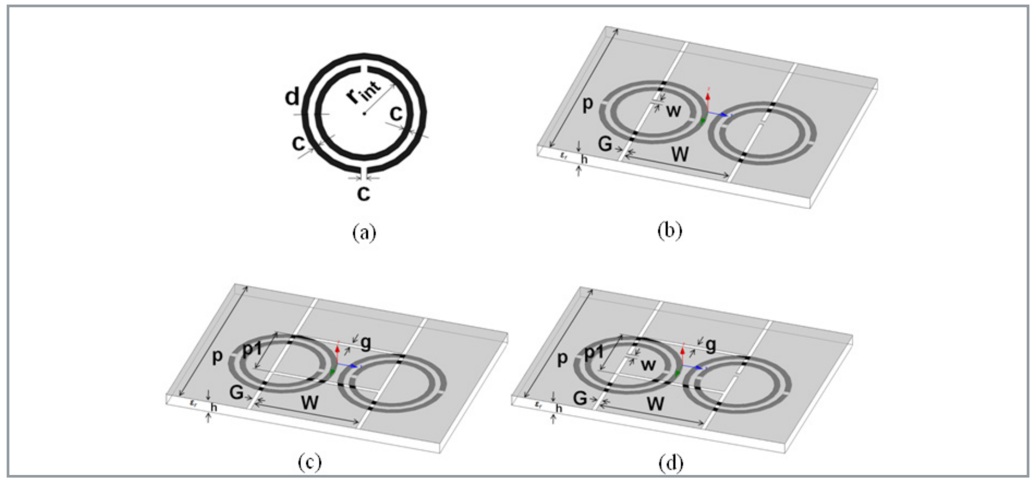
The frequency response of such structures generally presents a deep rejection just below the pass band, but poor selectivity and transmission band edges in the upper band. The former effect can be explained by the SRR resonance, while the latter is attributed to the smooth change of the SRR permeability from negative to positive values around the magnetic plasma frequency. Therefore, diverse approaches have been proposed to overcome this asymmetric response and its related drawbacks. For instance, a combined right/left handed CPW structure was implemented by means of cascading SRRs-wire and SRRs gap stages [63], satisfactorily leading to sharp cut-off transmission bands. However, the necessary rejection and bandwidth control was difficult to obtain. Furthermore, a new methodology for the design of compact planar filters in microstrip technology was proposed in [64]. It is based on filter stages consisting of the combination of CSRRs, series capacitive gaps, and grounded stubs through vias. By these means, it is possible to achieve the necessary flexibility

to simultaneously obtain quite symmetric frequency responses, controllable bandwidths, and compact dimensions. The cited structures exhibit excellent electrical behaviors, but at the same time different issues regarding selectivity, transmission band edges, or complex technology solutions like via holes can be further improved. Furthermore, based on CSRR particles, a wide range of devices with novel filtering properties have been developed [65-68].

In the following, Section 2 introduces three possible combinations of loading elements in SRR loaded CPW lines for improving their electrical response. Section 3 presents the results obtained for the different models in terms of simulated and measured transmission and reflection parameters. These results are discussed in Section 4 and 5 through an extraction procedure of effective parameters and the analysis of cascaded structures, respectively. Finally, the main conclusions of the work are drawn.

2. SRR-loaded CPW models

Figure 6 shows the three unit cells corresponding to different configurations of SRR-loaded CPW lines that have been considered in order to improve the control of their propagation characteristics.



■ **Fig. 6.** *Basic unit cell elements of the loaded CPW planar transmission lines: (a) SRR characteristic dimensions (r_{int} = 2.6 mm and c = d = 0.4 mm); schematic unit cells for (b) Model 1, (c) Model 2, and (d) Model 3 with relevant dimensions (w = 0.4 mm, p1 = 5 mm, and g = 0.25 mm). Note that SRRs are on the back plane of the dielectric substrate and that series gaps and shunt wires are on the top side of the substrate.*

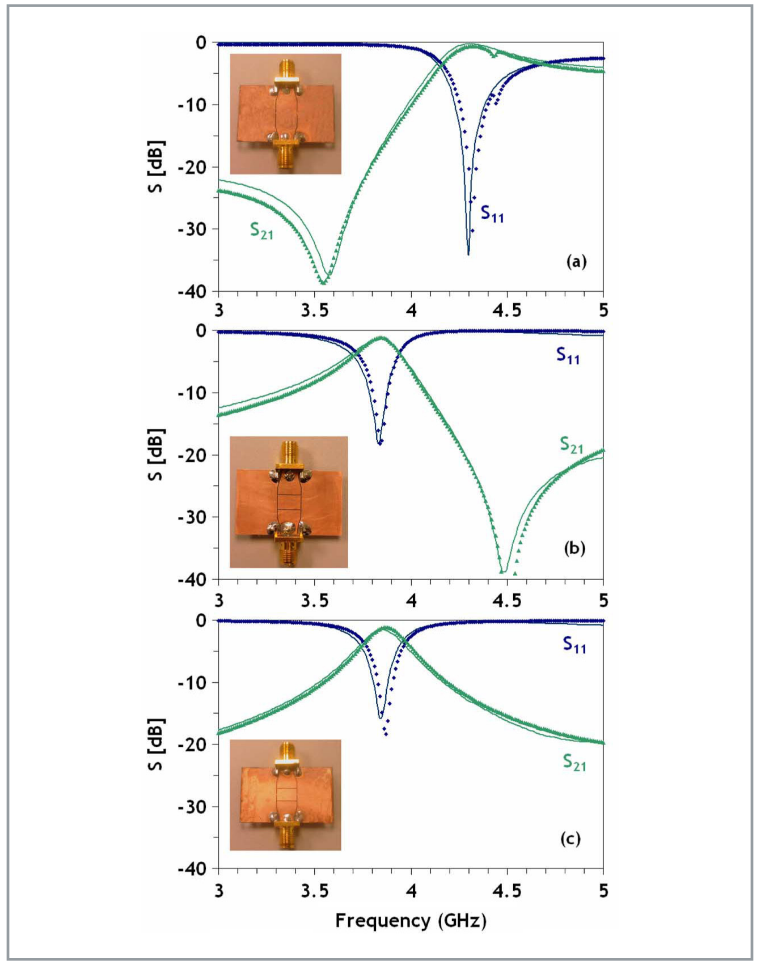
The first model is based on the combination of SRRs and shunt wires (Model 1). This resonant and LH propagation structure has been deeply analyzed [55]. Therefore, it is not the purpose of this paper to review the characteristics of this line, but rather to use it as a reference result. In short, this unit cell behaves as a LH propagation transmission line that can be described as a double-negative effective medium, if its size is sufficiently small as compared to the wavelength. The SRRs are responsible for a negative effective permeability effect, whereas shunt wires in the CPW provide a negative effective permittivity. Therefore, the structure can be considered double-negative just slightly above the resonance frequency of the isolated SRR.

The second model is based on the combination of SRRs and series gaps (Model 2). In this configuration, shunt wires on the upper side of the substrate have been replaced by series gaps. The latter can be considered as dual elements of the shunt wires and are symmetrically placed with respect to the center of the unit cell. Hence, the parallel inductive contribution of the wires is replaced by a series capacitance included in the line. Since both series gaps are, in turn, serially connected, the total capacitive contribution is halved with respect to that of a single series gap. The third model is based on the combination of SRRs, series gaps, and shunt wires (Model 3). It includes all loading elements previously introduced.

3. Simulation and Experimental Results

All prototypes have been fabricated on a Neltec NY9220 dielectric substrate (h = 0.508 mm, ε_r = 2.2, and tan δ = 0.0009). The CPW dimensions (W = 7.7 mm and G = 0.3 mm) have been selected in order to approximately define Z_0 = 50 Ohms access ports for the unit cell. The unit cell period has been set to p = 10 mm. Prototypes were fabricated using a mechanical milling process with an LPKF Protomat 93 S machine at iTEAM (Valencia). Measurements have been performed with a Rohde & Schwarz vector network analyzer ZVA-24 calibrated with a Through- Open-Short-Match kit, in the frequency band from 3 to 5 GHz.

Prior to experiments, the unit cell configurations have been analyzed with the full-wave solver HFSS based on the finite elements method (FEM) version 12. In terms of S-parameters (magnitude of S11 and S21), the results for the three cells are compared in Fig. 7. Agreement is found to be very good in all three cases. As principal features for each one of the models, it can be mentioned that Model 1 exhibits a pass-band centered around 4.3 GHz with a transmission zero close to 3.6 GHz. Model 2 exhibits a transmission band centered around 3.8 GHz and a transmission zero around 4.5 GHz. An important note here is that the SRRs are exactly the same in all configurations, and only the other loading elements (series gaps and shunt wires, not resonant by themselves in this frequency range) are different. Let us underline that by no means can the line portion in between the two series gaps be considered a resonator by itself since its length is electrically approximate to $\lambda g/14$ at 4 GHz. Therefore, this line portion resonates at much higher frequencies. Finally, Model 3 shows a very symmetric pass-band centered on 3.9 GHz with no transmission zeros in the vicinity. At the same time, rejection of this third structure below the transmission window is increased by 3 dB at 3 GHz with respect to Model 2. For Models 1 and 2, a sharp fall is only observed in the S21 curve between the transmission maximum and the transmission zero, not on the other side of the pass-band. The maximum transmission levels in the pass-band for Models 2 and 3 are lower than for Model 1. It can be shown that the discontinuities introduced by the series gaps slightly increase radiation losses and are the source of this minor degradation.



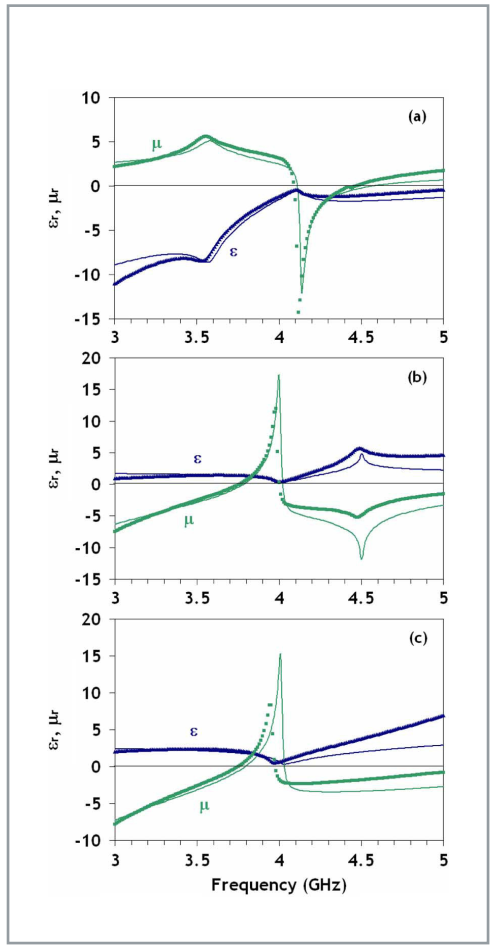
■ **Figure 7.** *Transmission (S21) and reflection (S11) coefficients for the three unit cells analyzed: (a) Model 1; (b) Model 2; (c) Model 3. Simulation (lines) and experimental results (symbols). Insets show the fabricated prototypes.*

4. Analysis of Propagation Characteristics and Extracted Parameters

The analysis of propagation features of the different devices is based on the retrieval of the effective medium parameters by the well-known Nicolson–Ross–Weir (NRW) procedure [69]. Nevertheless, it is also well known that this extraction procedure has to be applied with caution since it may produce inaccurate results. This is especially true in the presence of resonant elements and due to problems linked with causality. Let us note that for an operation frequency around 4 GHz, the electrical wavelength in the CPW is approximately $\lambda_g = 67$ mm. Therefore, the ratio unit cell period to electrical wavelength in our case is $p/\lambda g \approx 0.15$, giving a minimum guard to apply this homogenization procedure. Since one of the fundamental limitations of the NRW method is the use of electrically small structures, only unit cell calculations are used in our analysis; extractions on longer transmission lines may give imprecise results.

Our target is here to analyze the nature (electric and magnetic contributions) and specific features of the different propagation bands generated by the three models having the electrical responses displayed in Fig. 7. For this purpose, the frequency dependence of ε and μ, extracted from the experimental and calculated Sij for the three prototypes that were fabricated, are shown in Fig. 8. It can be found that for Model 1, a double-negative frequency band is generated between 4.1 and 4.5 GHz, corresponding to the LH band. In contrast, for Models 2 and 3, the pass-bands shown in Fig. 7 correspond to a double-positive condition. For these two models, the transmission bands are centered on a frequency lower than the center frequency of the transmission band of Model 1 (3.8 instead of 4.3 GHz). Considering that the SRR dimensions are identical in all three configurations, the resonant frequency of the isolated resonator is unchanged. Therefore, the generation of a passband in Models 2 and 3 is related to the high and positive permeability obtained below the resonance frequency of the SRR. In this case, the SRR is contributing to generate a dual right-handed (RH) transmission band as opposed to the situation of Model 1. It is also interesting to note that extracted permeability is negative for Models 2 and 3 outside the transmission band of Fig. 7.

This is due to the series capacitance response, which generates a negative permeability in the frequency range under study. This series capacitance precludes transmission outside of the area where the SRR resonates. Moreover, permittivity remains positive in the whole measured frequency band (3 to 5 GHz). This combination gives a positive refractive index $n = (\varepsilon\mu)1/2$ (for lines of Models 2 and 3). Note also, as expected, that peak transmissions correspond for all models to the different crossings of the ε and μ curves ($\varepsilon = \mu$ gives the matching condition and, hence, maximum transmission and minimum reflection). In addition, the analysis of the transmission phase of multiple cell devices proves that the refractive index sign for electrically long structures, where the parameter extraction may not provide accurate results, is in accordance with the results of Fig. 8. Finally, it can be noted that incorrect (noncausal) results can be achieved in the vicinity of the resonance frequency evidenced by incorrect signs of the slopes of the permittivity and permeability dispersion. Further details about the causality principle can be found in [70]. This restricts a little bit the frequency band where the validity criteria for an accurate parameter extraction are fulfilled.

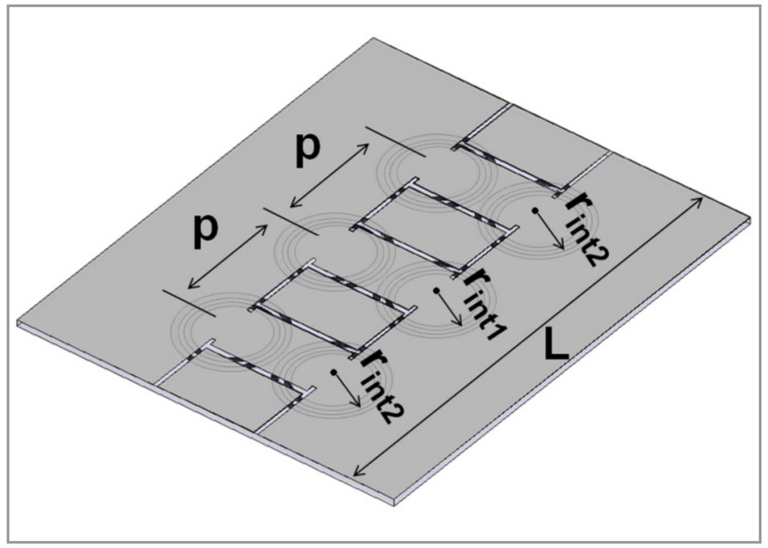


■ **Figure 8.** *Real parts of extracted permittivity and permeability: (a) Model 1, (b) Model 2, and (c) Model 3 according to the NRW method. Simulation (lines) and experimental results (symbols).*

5. Cascaded Structures

From filtering theory, it is well known that the steepness of the rejection out of the pass band can be greatly enhanced by cascading several cells. However, when the cascaded cells are in close proximity, it is also known that the pass band bandwidth broadens due to the cell coupling. The purpose of this section is to show that the sharpness of the out-of-band rejection can be greatly enhanced by serially connecting a number of cells after performing a proper optimization of the inner radius of the SRR resonators. The topology of the structures is presented in Fig. 9, where both loading elements, series gaps and shunt strips, are represented in the same model. The proposed structure consists of three SRRs stages with a total length of $L = 35$ mm.

The simulated responses of the 3-stages filters directly using the basic cells outlined in section 2, not shown here for the sack of space, presented a strong ripple feature along the pass band due to the interaction between the different stages. Also, the reflection coefficient represented by the S_{11} parameter reached poor values above – 10 dB. These drawbacks can be minimized by breaking the periodicity of the structure, and then optimizing the parameters of each stage independently. Two different ring resonators, with just different internal radius r_{int1} and r_{int2} are thus considered, as shown in Fig. 9.



■ **Figure 9.** *Schematic of the CPW line composed of 3 cascaded unit cells. All elements, SRRs, series gaps and shunt strips, are included.*

By varying the inner radius, the SRR slot width is modified and hence the resonance frequency of each resonator. In consequence, an optimization of the responses has been performed by means of two variables, the internal radius r_{int1} and r_{int2}, and the unit cell period *p* to achieve a reflection coefficient S_{11} below −10 dB along the pass band. The unit cell period and the SRR's radius

The properties of these structures can be controlled by properly de–signing the loading elements

control the distance between resonators, and then can reduce or increment the interaction between stages. Consequently, a modification of the ripple is expected. However, another different set of design variables could have been used for this optimization, such as the SRR strip width c, the shunt strip width w, or the distance between gaps p_l.

As it can be observed, a band pass response is obtained for all the three cases with insertion loss levels close to 2 dB. Also, narrow bandwidths are achieved with typical fractional bandwidth (FBW) values around 2.8 %. In this sense, even narrower bandwidths can be obtained (close to 0.8 %) by simply enlarging the strip/gap width or gaps distance. On the contrary, a degradation

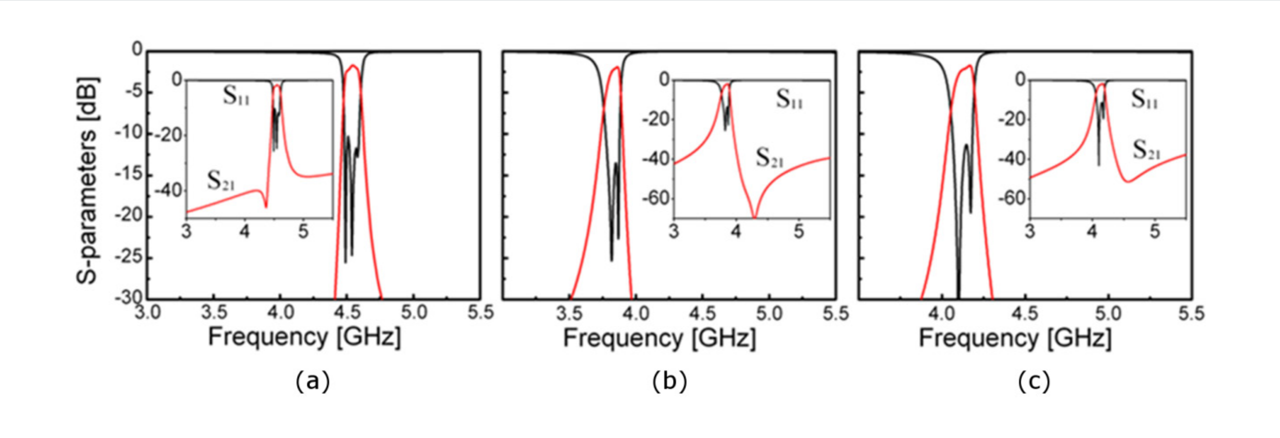


Figure 10. *Simulated frequency response of the 3-stages CPW filter loaded with a) shunt strips, b) series gaps, and c) series gaps and shunt strips.*

The frequency response of the optimized filters based on the three different cells is shown in Fig. 10. After performing the optimization processes, the dimensions obtained are: unit cell period p = 10.5 mm, radius of the central and external cells r_{int1} = 2.6 mm and r_{int2} = 2.584 mm and shunt strip width w = 3.5 mm for the 3 cells filter with only shunt strips; unit cell period p = 11 mm, radius of the central and external cells r_{int1} = 2.621 mm and r_{int2} = 2.6 mm, series gap width g = 0.4 mm and distance between gaps $p1$ = 5 mm for the 3 cells filter with just series gaps; finally, unit cell period p = 11 mm, radius of the central and external cells $rint1 = rint2$ = 2.6 mm, series gap width g = 0.25 mm, distance between gaps $p1$ = 5 mm and strip width w= 3.5 mm for the 3 cells filters with both series gaps and shunt strips.

of the insertion losses can be found. In addition, the out-of-band rejection reached at around 0.35 GHz from the central frequency is close to -30 dB (or better) at both sides of the pass band for all filters. At last, we can conclude that lower insertion losses are present when wide strips are used, since the absence of series gaps reduce the radiation losses through the open slots.

Finally, the advantage of miniaturization when SRRs loaded CPW lines are used can be clearly appreciated in Fig. 11. It compares dimensions of both simulated models, namely SRRs loaded CPW lines with wide shunt strips and conventional edge-coupled lines filters, as well as frequency responses for two different relative FBWs of 3% and 1%, respectively. The total length L_1 is roughly 35 mm (three times the unit cell period), whereas the length L_2 is approximately 68 mm. Thus, the proposed filters are shortened by a reduction ratio of 2.3.

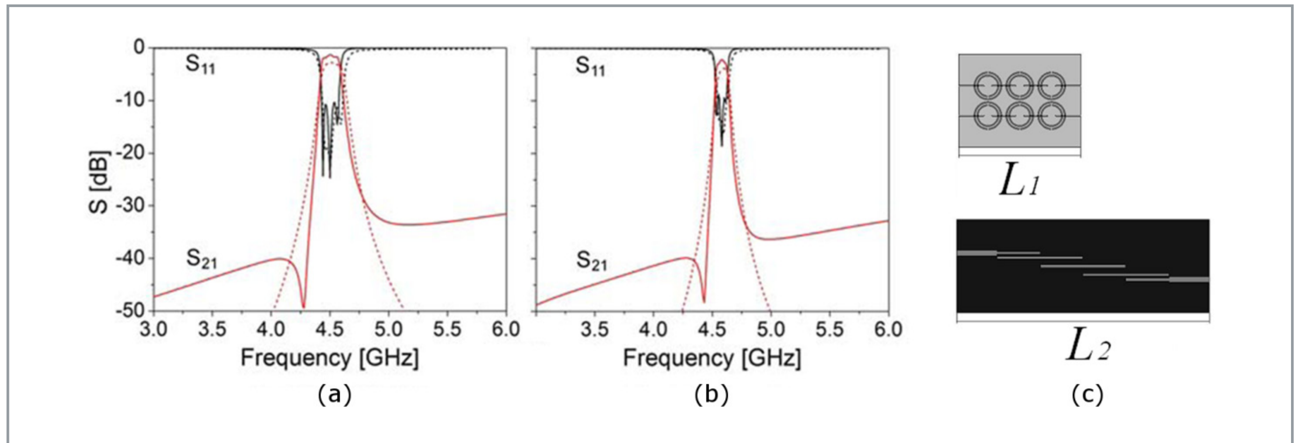


Figure 11. *Simulated S-parameters for the optimized 3 stage SRRs loaded CPW line with shunt strips and for a conventional order-3 edge-coupled filter with similar performance (dashed line). Filter response with a) 3 % FBW and b) 1% FBW. Layout comparison, L_1 = 35 mm and L_2 = 68 mm.*

In summary, the main advantages of the filters proposed are the small insertion losses obtained in very selective filters with compact dimensions. Also, the effective control of the frequency response characteristics makes these approaches very attractive for real applications. Specifically, FBW between 14% and 1% can be designed with acceptable tradeoffs between insertion losses and selectivity in all three structures. This excellent behavior can be attributed to the high quality factor of the resonator employed, which was found near 400 by eigen-mode simulations. Compared with conventional solutions [71], the high-Q frequency selective filters presented here can bring new degrees of freedom to obtain narrow band pass devices with good insertion losses and selective responses.

6. Conclusions

In this paper, three approaches of metamaterial-inspired planar filters with different loading elements have been proposed and discussed. Particularly, split ring resonators based coplanar waveguides have been loaded with series gaps or/and shunt strips. A left-handed medium is provided for shunt strips loaded lines, whereas a right-handed media is achieved when just series gaps or series gaps combined with shunt strips are exploited. The properties of the different basic cells were experimentally demonstrated by means of fabricated prototypes. In addition, the use of extracted parameters helps to explain and design loaded transmission lines based on resonant elements. It was shown that suitably optimized cascaded structures can effectively achieve improved performances in terms of insertion losses and rejection features. To conclude, the good performance obtained for these planar filters can be ascribed to the high quality factor of the resonator employed.

Potential use of these miniaturized high-Q frequency selective cells can be foreseen in many application fields, notably for biosensors relying on a resonance frequency shift and planar frequency filtering structures with severe specifications.

Acknowledgment

The authors acknowledge the assistance of Mr. Antonio Vila (fom GRE, iTEAM) in the fabrication of the prototypes and the financial support of MEC-Spain (TEC 2007/67630-C03-01 project), EGIDE-France ("Acción Integrada–Picasso" project), Centre National d'Etudes Spatiales (CNES) in France and Generalitat Valenciana (Project No. GV/2007/215).

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