Novel Metamaterial-Inspired Planar Cells for Compact Filtering Applications

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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 \( \mathbf{k} \) would be anti-parallel to the direction of the Poynting vector \( \mathbf{S} \). Consequently, while energy still travels away from the source, wave fronts travel backward towards the source. This is distinctly different from the isotropic medium with positive \( \varepsilon \) and \( \mu \), 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 \( (\varepsilon, \mu, \mathbf{k}) \). These structures produce a magnetic response resulting 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 gaps, the properties of the loaded Q quality factors, is pointed out. Enhancing the loaded Q quality factors, and the reversal of the Doppler shift and advancement, and the damping of the frequency. From this equation, theory predicts a negative permeability in 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.

\[
\mu_{\text{eff}}(\omega) = 1 - \frac{F a^2}{\omega^2 - \omega_0^2 + i \gamma \omega}
\]

In equation (3), \( \omega \) is the angular frequency, \( F \) the filling factor with material that is magnetically active, \( \omega_0 \) the resonant frequency, and \( \gamma \) the damping of the frequency. From this equation, theory predicts a negative permeability in a small frequency range above the resonant frequency \( \omega_0 \).

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

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 gaps, the properties of the loaded Q quality factors, is pointed out. Enhancing the loaded Q quality factors, and the reversal of the Doppler shift and advancement, and the damping of the frequency. From this equation, theory predicts a negative permeability in 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.

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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 a negative index of refraction 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.

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 antenna media could achieve the left-handed propagation were firstly reported 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.

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 rejetion 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 via. 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 behavior, but at the same time different issues regarding selectivity, transmission band edges, or complex technology solutions, like via microstrip or planar waveguides proved. 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.
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), resonant by themselves in this frequency range are different. Let us underline that by no means can the line portion in between the two well-known gaps be considered a resonator by itself since its length is electrically approximate to \( \lambda/4 \) 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.

### 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 \( \lambda_e = 67 \) mm. Therefore, the ratio unit cell period to electrical wavelength in our case is \( \pi/\epsilon \approx 0.15 \), 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 \( \epsilon \) and \( \mu \) 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 pass-band 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 and 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 produces transmission outside of the area where the SRR resonates. Moreover, permittivity remains positive in the whole measured frequency band to 5 GHz. This combination gives a positive refractive index \( n = (\sqrt{\mu}\epsilon) \) for line of Models 2 and 3. Note also, as expected, that peak transmissions correspond for all models to the different crossings of the \( \epsilon \) and \( \mu \) curves (\( \epsilon \approx \mu \) 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 in incorrect (non-causal) 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 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.](image)

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 response has been performed by means of two variables, the internal radius \( r_{\text{int1}} \) and \( r_{\text{int2}} \) and the unit cell period \( p \) to achieve a reflection coefficient \( S21 \) below –10 dB along the pass band. The unit cell period and the SRR’s radius 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.](image)

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 lack 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 \( S21 \) 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 \( r_{\text{int1}} \) and \( r_{\text{int2}} \) are thus considered, as shown in Fig. 9.

![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).](image)
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, the shunt strip width, or the distance between gaps . 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 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 FBW of 3% and 1%, respectively. The total length , is roughly 35 mm (three times the unit cell period), whereas the length , is approximately 68 mm. Thus, the proposed filters are shortened by a reduction ratio of 2.3.

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 the approach 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 resonant elements which were used. It was found near 400 by eigen-mode simulations. Compared with conventional solutions [71], the high-Q frequency selective filters considered here can now 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 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 coplanar 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. As a consequence, 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 applications fields, notably for biosensors relying on a resonance frequency shift and planar frequency filtering structures with severe specifications.

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Frequency selective properties. Since 2009, he is the design of metamaterial based structures with新颖 algorithms or structures.

In the design of metamaterial based structures with novel algorithms or structures, he has been the organizer of several workshops and conferences mainly on metamaterials in the framework of the novel infrastructure IRCICA, funded by CNRS. Prof. Lippons has authored and co-authored more than 150 journal papers and supervised 30 PhD’s. His current research interest includes EM metamatals, antennas, tunable structures and their applications in microwave and millimeter-wave technologies.

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