Invited paper

Miniaturization of Planar Microwave Devices by Means of Complementary Spiral Resonators (CSRs): Design of Quadrature Phase Shifters

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Abstract. *In this work, two compact quadrature phase shifters based on metamaterial transmission lines implemented by means of complementary spiral resonators (CSRs) have been designed, fabricated and measured. The structures consist on Y-junctions with output lines exhibiting 90º phase balance. The reported metamaterial-based devices present a size reduction of 64% and 77% as compared to the conventional one.*

Keywords

Metamaterials, Complementary Spiral Resonators (CSRs), Phase Shifters.

1. Introduction

Planar microwave components exhibit, generally, large dimensions. Several techniques have been presented in order to miniaturize these devices. An example could be the use of semi-lumped capacitors, inductors and resonators for the design of microwave filters [1]. In recent years, the use of metamaterial-based transmission lines, consisting on a host line loaded with reactive elements, is another alternative to achieve a high degree of miniaturization. This is due to their small electrical length. Moreover, these lines exhibit a controllable dispersion diagram which is of interest for the design of microwave devices with enhanced bandwidth or dual-band operation, based on dispersion engineering.

It is well known that there are two main approaches for the synthesis of metamaterial transmission lines: i) the CL-loaded approach, where a host line is loaded with series capacitances and shunt inductances [2-4], and ii) the resonant-type approach, where the loading elements are split ring resonators (SRRs) [5], or their complementary counterparts, that is, the complementary split ring resonators (CSRRs) [6].

In previous works developed by some of the authors, the resonant-type approach has been used not only to design miniaturized filters [7] and other microwave components [8], but also to obtain devices with improved characteristics or novel functionalities, like enhanced bandwidth [9] and dual band components [10]. The great potential of this kind of lines for their application in microwave components has been clearly demonstrated with the presented examples. Further miniaturization can be obtained by means of particles derived from the SRR: the spiral resonator (SR) and the three turns spiral resonator (SR3) [11]. Topologies and their equivalent circuits are represented in Fig. 1 [12], where C_0 is the edge capacitance between the two rings over the whole circumference, and L_s is the inductance of a single ring and average radius, as described in [12].

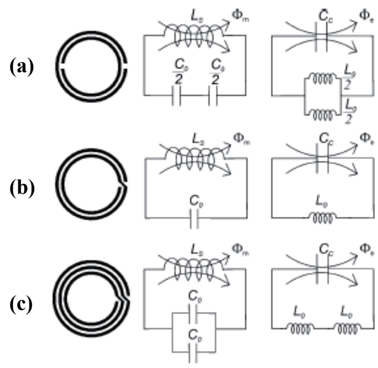
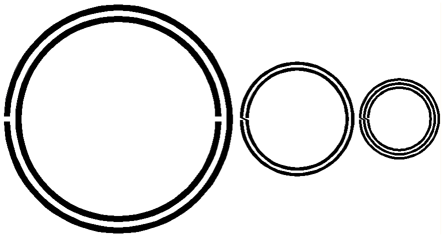


Fig. 1. SRR (a) and particles derived from the SRR: b) the SR and c) the SR3. The equivalent circuit models are depicted in the second column and the models for the complementary counterparts are in the third column. Extracted from [12].

From the equivalent circuits, it can be seen that there is a reduction of the resonance frequency with respect to the SRR. The capacitance value for a SRR is $C_0/4$, whereas for a SR is C_0 and for a SR3 is $2C_0$. So, the resonance frequencies ratios are:

$$f_{0SRR} \approx 2 f_{0SR} \approx 2\sqrt{2} f_{0SR3} \,. \tag{1}$$

It is obvious that we obtain a smaller particle for the same desired resonance frequency using these topologies. Comparing the sizes of SRR, SR and SR3 presenting the same resonant frequency we can see that the reduction factor is about 50% for the SR and 65% for the SR3 as compared to the SRR (Fig. 2). These miniaturized particles have been used for the design of artificial magnetic metamaterial media [13].



(a) (b) (c)

Fig. 2. Comparison between a SRR (a), a SR (b) and a SR3 (c) presenting the same resonance frequency. The reduction factors are approximately 50% and 65% with respect to the original SRR.

To synthesize artificial resonant-type transmission lines in microstrip technology, we should use the complementary counterparts of these particles. A typical unit cell based on a complementary spiral resonator (CSR) and its equivalent circuit model are depicted in Fig. 3. This circuit model is the same for the CSRR-based cells, but it is depicted here for completeness. L is the line inductance, C_g depends on the capacitive gap, the CSR etched on the ground plane is modeled by the L_c-C_c resonant tank, and C represents the coupling between the line and the resonator (including the line capacitance and the fringing capacitance corresponding to the series gap) [14]. At low frequencies, the loading elements are dominant and wave propagation is backward (left-handed). At higher frequencies wave propagation is forward (right-handed), because the dominant elements are those that model the host line. These two transmission bands are usually separated by a gap, which can be collapsed by forcing the series and shunt resonance frequencies of the T-circuit model to be equal, obtaining a balanced cell [15]. Using this case it is possible to design zero-degree transmission lines.

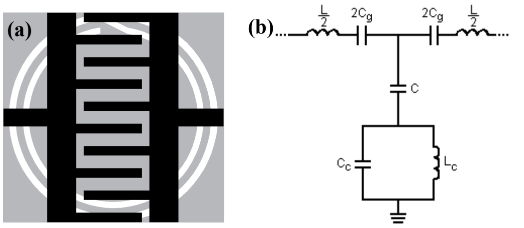


Fig. 3. Unit cell of the CSR-based artificial line (a) and equivalent T-circuit model (b). Top metal is depicted in black, whereas bottom metal is depicted in gray.

In Fig. 3(a), it can be seen that the series capacitance is implemented by means of an interdigital structure. This indicates that we need a higher value of C_g as compared with the CSRR-based implementation, due to the reduction of line inductance (the use of miniaturized resonators only makes sense if the length of the host line is also reduced), to preserve the required electrical characteristics. In this work, this structure is used for the design of compact power dividers with output lines exhibiting a 90º phase difference, which will be called quadrature phase shifters from now on.

2. Design of Compact Quadrature Phase Shifters

The considered phase shifter consists on a Y-junction with a 90º admittance inverter, presenting a characteristic impedance of 35.35 Ω to preserve the input matching, and output lines that exhibit a phase difference of 90º at the frequency of interest. In the conventional device the output lines have an electrical length of +90º and +180º and a characteristic impedance of 50 Ω (Fig. 4a). In this paper, two variations of this topology are presented: i) output lines replaced with artificial cells, and ii) output lines and admittance inverter replaced by artificial cells. The design frequency for all these devices is 1.55 GHz.).

2.1 Quadrature Phase Shifter with Metamaterial Output Lines

In this case, only the 50 Ω output lines are replaced by a −90º left-handed cell and a 0º balanced cell (setting the series and shunt resonance frequencies of the equivalent circuit model to be equal at the design frequency) [15], thus preserving the 90º phase balance provided by +90º and +180º output lines in the conventional device. This idea was implemented before by the authors, designing the device by means of CSRR-based cells for the same frequency, and obtaining an enhanced bandwidth phase balance response (Fig. 4b) [16].

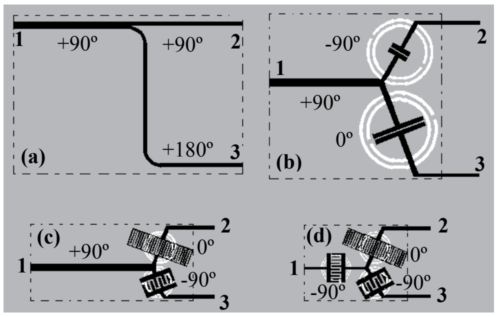


Fig. 4. Comparative layouts (drawn to scale) of the four quadrature phase shifters: conventional (a), CSRR-based (b) [16], device with two CSR-based cells (c), device with three CSR-based cells (d). Top metal is depicted in black, whereas bottom metal is depicted in gray. All devices have been implemented on the *Rogers RO3010* substrate with ε_r = 10.2 and thickness h = 635 μm. The active area is indicated by means of a dashed rectangle. The reduction factors, as compared with the conventional implementation, are 20%, 64% and 77%, respectively.

In order to design the CSR-based metamaterial transmission lines, we must set the desired phase ϕ and characteristic impedance Z_B at the frequency of interest. These parameters are given by:

$$\cos\phi = 1 + \frac{Z_s(\omega)}{Z_p(\omega)}, \qquad (2)$$

$$Z_B = \sqrt{Z_s(\omega)[Z_s(\omega) + 2Z_p(\omega)]} \qquad (3)$$

where Z_s and Z_p are the series and shunt impedances of the T-circuit model. From these equations, and following the procedure described in [8] it is possible to design the desired artificial lines. The dimensions of the –90º cell are: line length l=5.07 mm, line width w=0.56 mm, CSR external radius r_{ext}=2.44 mm, spiral width c=0.22 mm, spiral separation d=0.22 mm and the interdigital capacitor is formed by 8 fingers separated 0.26 mm. For the 0º cell, dimensions are: l=6.68 mm, w=0.56 mm, r_{ext}=2.43 mm, c=0.21 mm, d=0.20 mm and 28 fingers separated 0.16 mm forming the interdigital capacitor. The proposed phase shifter is shown in Fig. 4c, and the simulation and measurements of the power splitting and phase balance for the device are shown in Fig. 5. The shift between measurement and simulation is mostly attributed to a variation of the dielectric constant of the substrate and to fabrication related tolerances. It has been verified from measurement that the substrate dielectric constant is 15% higher than the nominal value, which explains in part the shift towards smaller frequencies in measurement. In this case, it has not been possible to enhance phase balance bandwidth. As has been pointed in Section 1, it is necessary a higher value of C_g with respect to CSRR-based cells to obtain the required characteristics. In this way, the gap capacitance value required to balance the 0º cell is much higher than the value required for the –90º cell, and this makes difficult to achieve similar slopes in the phase responses of each cell (as it is required to enhance bandwidth), with the consequence of a higher derivative of the phase difference with the frequency.

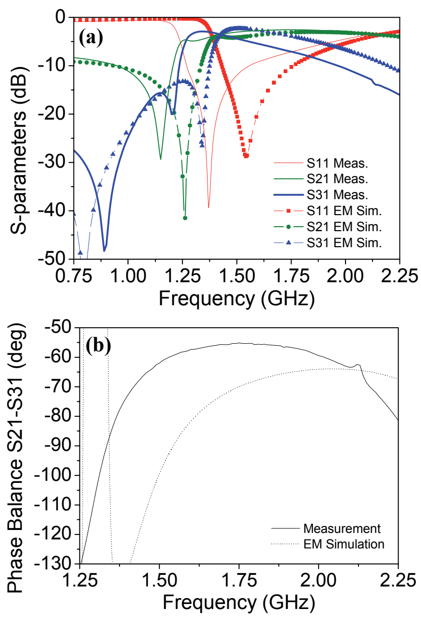


Fig. 5. Simulated and measured power splitting and matching (a) and phase balance (b) for the device of Fig. 4(c).

2.2 Quadrature Phase Shifter with Metamaterial Output Lines and Admittance Inverter

In [14], the admittance inverter was not replaced with a metamaterial-based one in order to enhance bandwidth. In the present case, we have seen that it is not possible to enhance bandwidth using CSR-based cells, so the 35.35 Ω admittance inverter could be also replaced with a –90º left-handed line in order to achieve further miniaturization. Dimensions of this new cell are: l=9.55 mm, w=0.37 mm, r_{ext}=2.26 mm, c=0.15 mm, d=0.16 mm and 10 fingers separated 0.28 mm forming the interdigital capacitor. This metamaterial-based admittance inverter presents a length of 0.13λ (where λ is the guided wavelength at the design frequency). The CSR-based cell topology allows us to design even a shorter line (the –90º and 50 Ω output line is 0.07λ), but there is the need of correctly connect the three cells to implement the device. The proposed phase shifter is shown in Fig. 4d, and the simulation and measurements of the power splitting and phase balance for the device are shown in Fig. 6. As in Fig 5, a frequency shift between measurement and simulation can be appreciated, and it is attributed to the same factors.

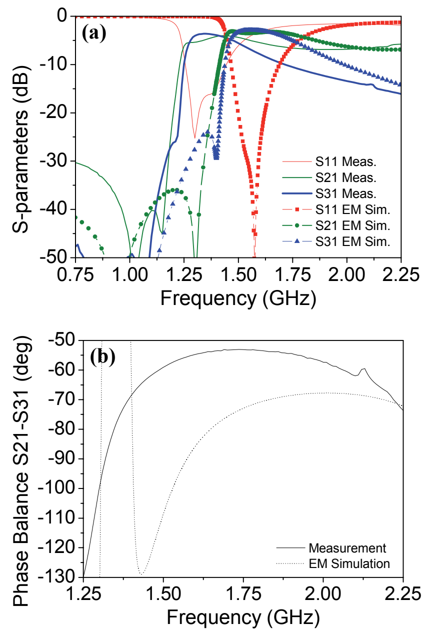


Fig. 6. Simulated and measured power splitting and matching (a) and phase balance (b) for the device of Fig. 4(d).

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Gerard SISÓ was born in Barcelona in 1981. He received the Industrial Engineering Diploma, specializing in Electronics from the Universitat Politècnica de Catalunya in 2004 and the Electronics Engineering degree from the Universitat Autònoma de Barcelona in 2006. He is now working toward his PhD degree. His research interests include microwave circuits based on metamaterial transmission lines, especially enhanced bandwidth and multiband devices.

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Ferran MARTÍN was born in Barakaldo (Vizcaya), Spain in 1965. He received the B.S. Degree in Physics from the Universitat Autònoma de Barcelona (UAB) in 1988 and the PhD degree in 1992. From 1994 up to 2006 he has been Associate Professor in Electronics at the Departament d'Enginyeria Electrònica (Universitat Autònoma de Barcelona), and from 2007 he is Full Professor of Electronics. In recent years, he has been involved in different research activities including modeling and simulation of electron devices for high frequency applications, millimeter wave and THz generation systems, and the application of electromagnetic bandgaps to microwave and millimeter wave circuits. He is now also very active in the field of metamaterials and their application to the miniaturization and optimization of microwave circuits and antennas. He is the head of the Microwave and Millimeter Wave Engineering Group (GEMMA Group) at UAB, coordinator of the Spanish Network on Metamaterials (REME) and a partner of the Network of Excellence of the European Union METAMORPHOSE. He has organized several international events related to metamaterials, including a Workshop at the IEEE International Microwave Symposium (years 2005 and 2007). He has acted as Guest Editor for two special issues on metamaterials in two international journals. He has authored and co-authored over 230 technical conference, letter and journal papers and he is co-author of the monograph on metamaterials entitled Metamaterials with Negative Parameters: Theory, Design and Microwave Applications (John Wiley & Sons Inc.). Ferran Martín has filed several patents on metamaterials and has headed several Development Contracts. He has recently launched CIMITEC, a research Center on Metamaterials (supported by CIDEM - Catalan Government) where he acts as Director. Dr. Ferran Martín and CIMITEC have received the 2006 Duran Farell Prize for Technological Research.