# Balanced Right/Left-Handed Coplanar Waveguide with Stub Loaded Split Ring Resonators

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***Abstract*—In this letter, a host coplanar waveguide (CPW) loaded with modified Split Ring Resonators (SRR) is presented. In recent publications, it has been demonstrated that the capacitive interaction between the host CPW line and the SRRs is the cause of a right-handed band, which degrades the selectivity of the response. Consequently, an open-ended microstrip stub connected to the rings is used to modify this interaction, and thus have an effective control of the rejection above the pass band. Fortunately, these stubs only affect the frequency position of the right-handed band. As a result, it is quite straightforward to obtain Balanced Composite Right/Left-Handed (CLRH) transmission lines with increased transmission bandwidth and improved rejection levels, which are the main drawbacks of traditional SRR loaded CPW lines. Besides, the response of the modified cell shows a pair of transmission zeros at both sides of the passband. Therefore, this new cell is a very interesting choice for designing balanced CLRH lines and very attractive for filter applications.**

***Index Terms*—Double-negative materials, left-handed (LH) transmission lines, metamaterials, balanced right/left-handed, Coplanar waveguide (CPW), Split Ring Resonator (SRR), filters**

## I. Introduction

Interest and applications of left-handed transmission lines have widely grown in the last years, due to their unique properties [1]–[3]. When using a CPW as a host line, left-handed propagation is obtained by means of the well-known Split Ring Resonators [4], [5]. Using this kind of circuits it is possible to achieve very compact basic cells with reasonable selectivity. Besides, if this circuit is balanced by means of adjusting the right and left-handed propagation bands, an important bandwidth increase can be expected [6], [7]. Usually, in order to obtain a balanced line, only the host line is modified [6]–[8]. On the contrary, in this letter an artificially balanced line is obtained by means of exclusively altering the SRR. This strategy was already exploited in [9], where the SRR geometry was modified to synthesize a dual balanced CLRH line [10].

In this letter, an open-ended microstrip stub connected to the SRR is proposed to control the frequency position of the right-handed band, which also keeps the left-handed one unaltered. This effect can be explained by an originally capacitive interaction between the host line and both SRR, demonstrated previously in [11]. This interaction is modified with the new proposed stub, and as a result, the right-handed band can be shifted in frequency. Moreover, the response of the proposed cell exhibits an additional transmission zero above the pass band obtained from the composite performance of SRR loaded lines [12]. Due to this new transmission zero, this line is even more selective than the one presented in [9]. Consequently, this new cell is not only suitable for developing artificial balanced right/left-handed lines, but also very attractive for filter applications providing easily tunable frequency responses, highly symmetric selectivity, high rejection out the pass band and an acceptable level of insertion loss. Moreover, the new proposed artificial transmission line can be useful for designing advanced feeding networks of printed radiating elements as described in references [13]–[16].

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## II. Capacitively Loaded Cell Description

The new cell proposed in this letter is shown in Fig. 1(b). As mentioned in the previous section, it incorporates a pair of microstrip open-ended stubs connected to the outer rings of the SRRs. The starting point of this design is the classical SRR loaded CPW cell (Fig. 1(a)), which has been tuned at 3 GHz using the procedure highlighted in [1].

The characteristic impedance of the main CPW is 50 Ω. The cell has been designed for a Rogers 4003™ substrate ($\epsilon_r$

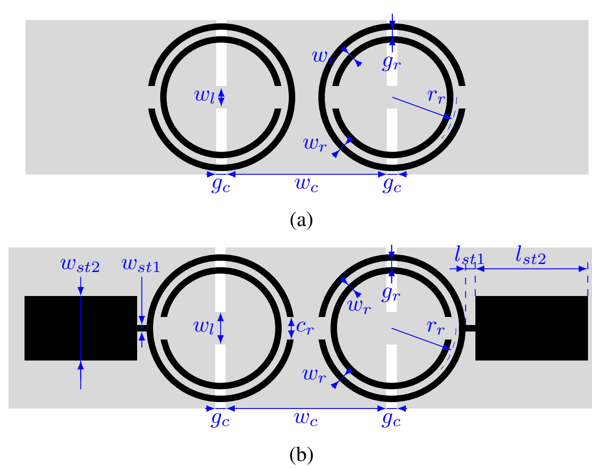


Fig. 1. (a) Basic cell [4]; (b) proposed cell with stub loaded SRR. The top layer is depicted in gray color, and the bottom layer in black.

=3.55) of 1.524 mm thick and 35 $\mu$m of copper metallization. The cell dimensions are shown in Table I.

TABLE I
CELL DIMENSIONS.

| | | | | | |
|---|---|---|---|---|---|
| $r_r$ | 3.88 mm | $w_{st1}$ | 0.30 mm | $l_{st1}$ | 0.60 mm |
| $w_r$ | 0.40 mm | $w_{st2}$ | 8.00 mm | $w_l$ | 1.00 mm |
| $g_r$ | 0.42 mm | $w_c$ | 10.0 mm | $l_{st2}$ | 14.9 mm |
| $c_r$ | 0.80 mm | $g_c$ | 0.65 mm | | |

The next step in the design is a parametric analysis affecting the stub length $l_{st2}$, performed with the commercial software Ansys HFSS™. The simulated model has been excited with waveguide ports, while a radiation box has been used to simulate the boundary conditions. The curves obtained are represented in Fig. 2. The parametric analysis clearly shows that the position of the right-handed band, that appears above 3 GHz, can be controlled with the stub length. On the other hand, the position of the original left-handed band, that is below 3 GHz, is not affected by this stub. The effect of stub width $w_{st2}$ has also been analyzed (Fig. 3), this analysis shows that the stub width is related with the slope of upper bandpass-to-stopband transition. From the previous parametric studies, the most appropriate combination of width and length for the proposed stub has been selected, and these values are included in Table I. As it can be seen, the design of the cell is easy and simple. Firstly, the left-handed band is tuned by means of the SRR characteristic parameters. Secondly, the right-handed band is modified by means of the stub length and width.

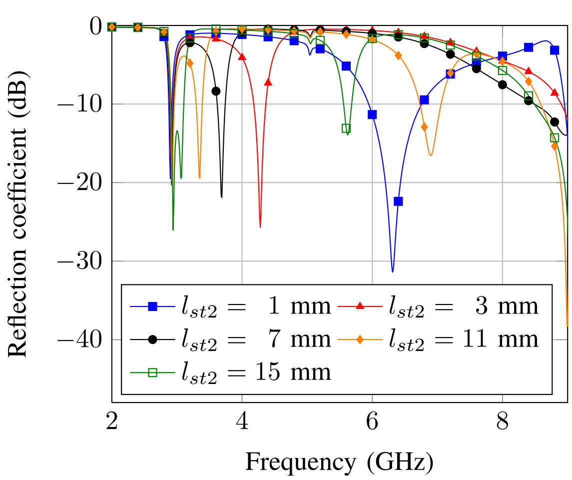


Fig. 2. Parametric analysis of the basic cell modifying the stub length.

An accurate equivalent circuit description of this kind of cells provides deeper insights into the physical interactions happening in the structure, and it can be used to easily obtain a good initial approximation to the desired response. The equivalent circuit proposed for this new cell can be seen in Fig. 4. To begin, the values of the equivalent circuit components and constant coupling have been obtained following the steps and formulation described in reference [1]. Subsequently, the microstrip stubs have been modelled using a circuit formed

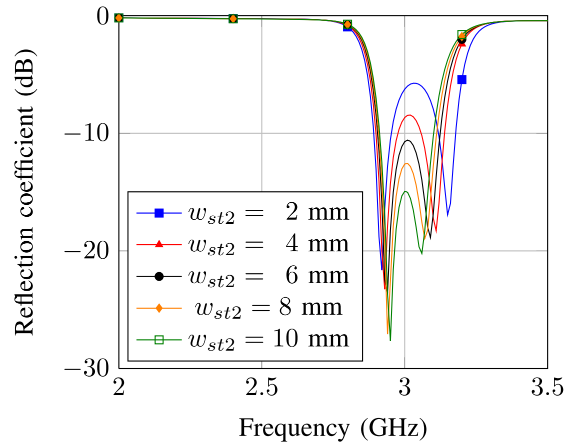


Fig. 3. Parametric analysis of the basic cell modifying the stub width.

by $L_{st}$ and $C_{st}$ since the stub length is close to $\lambda/4$. It has been calculated following the recommendations found in [17]. Moreover, it should be noted that the proposed SRR is asymmetrical as just one of the rings is loaded with the stub. As a result, only one parallel LC circuit is connected in derivation with the $C_g$ capacitor (the one connected with the ground plane). As it can be observed in Fig. 2 and Fig. 3, the stub inductance $L_{st}$ and capacitance $C_{st}$, that can be determined by the physical parameters $l_{st2}$ and $w_{st2}$, are responsible of the right-handed control. More specifically, the coupling between the stub and the lateral CPW ground planes, modeled with $C_{st}$, adjusts the right handed band shift. The higher this coupling is, the lower the right-handed band is shifted towards lower frequencies. In addition, the inductance of the stub denoted as $L_{st}$ modifies the slope above the pass band.

Once the equivalent circuit values have been estimated, these initial values have been slightly tuned by optimization in order to exactly match the equivalent circuit and cell responses. A quasi-newton method was employed with to minimize difference towards simulated scattering parameters using the next specific goals $\mid S_{11circuit} - S_{11sim} \mid \leq 0.01$ and $\mid S_{21circuit} - S_{21sim} \mid \leq 0.01$. The first goal is useful to match the responses within pass band. On the other hand, the second goal helps to match the responses out of the pass band. These values, estimated and optimized, are shown in Table II

TABLE II
EQUIVALENT CIRCUIT ELEMENTS

| | Estimated values | Optimized values |
|---|---|---|
| $L_{lo}$ | 1.737 nH | 1.536 nH |
| $C_{lo}$ | 0.6934 pF | 0.6224 pF |
| $L_{lr}$ | 1.741 nH | 1.540 nH |
| $C_{lr}$ | 0.6934 pF | 0.6240 pF |
| $L_p$ | 0.4 nH | 0.4659nH |
| $L_a$ | 18.75 nH | 18.56 nH |
| $C_a$ | 0.3488 pF | 0.3281 pF |
| $C_g$ | 0.9778 pF | 1.004 pF |
| $L_{st}$ | 1.25 nH | 1.804 nH |
| $C_{st}$ | 2.3 pF | 3.278 pF |
| $k$ | 0.3755 | 0.3643 |
| $Z_0$ | 50 Ω | 50 Ω |

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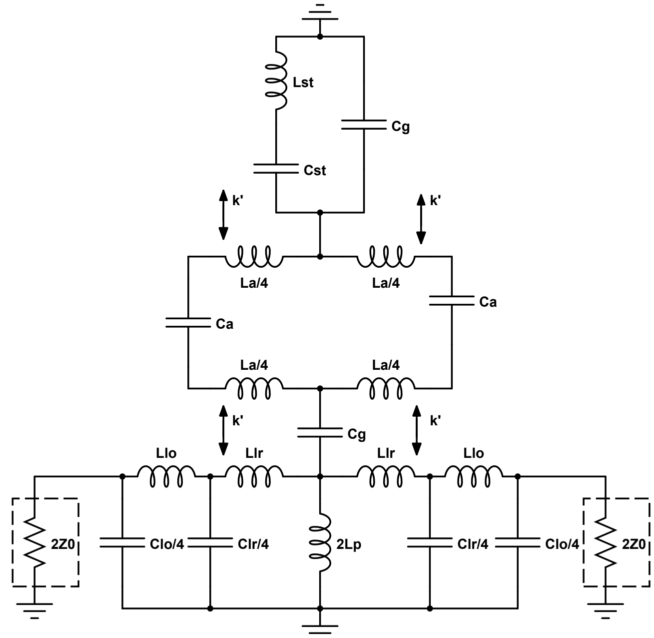


Fig. 4. Equivalent circuit considering the open-ended microstrip stub connected to the rings. Dots in inductances indicate the polarity of the inductive coupling, the coupling coefficient is positive.

## III. Results

In order to validate the proposed novel cell, a prototype has been manufactured, as shown in Fig. 5. SMA connectors have been added to measure this circuit in an Anritsu MS4642A Vector Network Analyzer (VNA). The connentors are soldered to a feeding line of input impedance 50 Ω. This line is 5 mm width with a gap of 0.477 mm. The taper is just a linear transition of 2.7 mm length between the feeding line and the SRR loaded line. During the manufacture process, the overmilling resulted in a frequency shift of the cell response. To compensate for these manufacturing tolerances, the SRR raidus in the simulation model was modified to $r_r$=4.19mm.

Fig. 6 and Fig. 7 show the scattering parameters of the proposed cell. Fig. 6 compares the equivalent circuit response and the one provided by the full-wave simulation not considering losses. Fig. 7 compares the full-wave simulation, taking into account losses and overmilling, and the measured response. The experimental results were obtained using a TRL calibration kit. It is composed of a transmission line of 30 mm (Line), a shorter transmission line of 14.5 mm (Thru) and a shorted line of 7.25 mm (Reflect). The agreement obtained between the proposed circuital model, the simulations and the experimental results is excellent. It validates both the equivalent circuit and full-wave simulations.

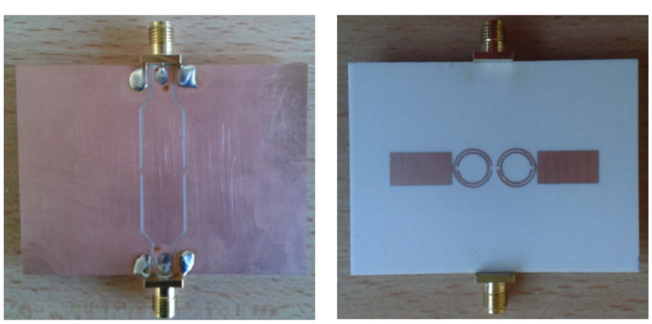

Fig. 5. Fabricated prototype. Left, top layer; right, bottom layer.

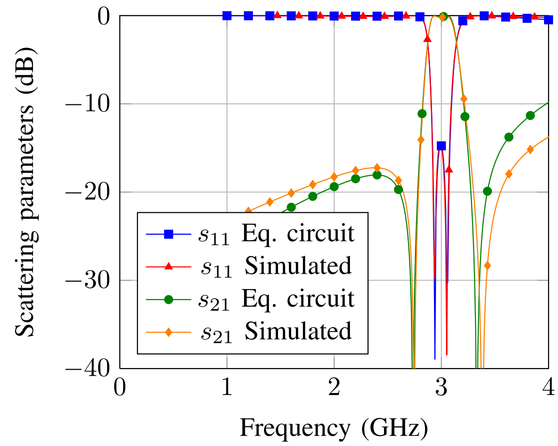


Fig. 6. Response of the basic cell without losses.

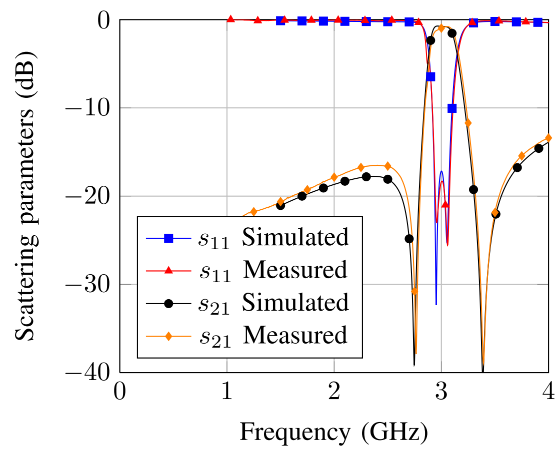


Fig. 7. Response of the basic cell considering losses.

Comparing the results to just the original unitcell without stubs [4], a bandwidth increase from 2.5% to 8.9% is observed. Moreover, the insertion loss of 0.86 dB at 3 GHz is acceptable for filter applications. In comparison with the cell proposed in [9], the response of the stub loaded cell exhibits a transmission zero above the pass band, and as a result, the selectivity and the rejection near the pass band are considerably improved. This new transmission zero is the dual counterpart of the transmission zero at the lower stop-band, and it can be explained from the dual nature of right- and left-handed passbands [12].

Finally, the left-handed behaviour of the cell is analysed. The dispersion diagrams have been calculated following the procedure explained in [18], see Fig. 8. Slightly under the passband central frequency, it can be seen that the phase decreases as frequency increases, therefore a left-handed propagation is obtained. Then, above the passband central frequency, the phase increases as frequency rises, and a right-handed propagation occurs. Both bands are almost overlapped with a smooth transition, so this fact confirms the balanced behaviour of this artificial line.

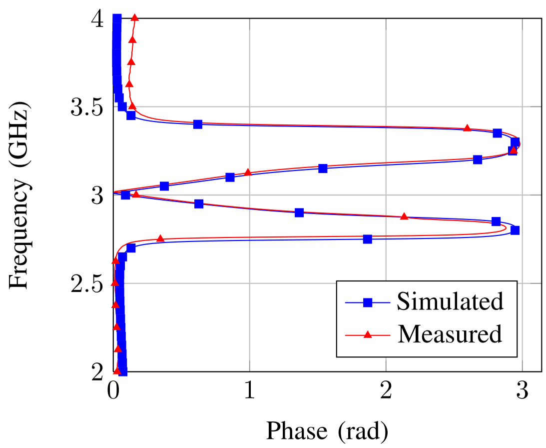


Fig. 8. Demonstration of the balanced behaviour of the cell: dispersion diagram.

## IV. Conclusions

In this letter, a strategy to design a balanced SRR loaded CPW composite line has been proposed. A microstrip open-ended stub connected to the SRR ring has been incorporated to the former CPW left-handed cell layout and is shown to modify only the right-handed bands features, such as insertion loss levels and frequency position. As a result, the original right-handed band can be shifted in frequency without affecting the left-handed propagation, so that a balanced cell can be easily designed by simply adjusting the proposed stub length and width. The response obtained presents better bandwidth and selectivity than former designs, and this cell can be a very promising choice for filtering applications, CLRH transmission line, and feeding networks designs.

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