Electric Split-Ring Resonator Based on Double-Sided Parallel-Strip Line

Luyu Wang, *Student Member, IEEE,* Xian Qi Lin, *Member, IEEE*

***Abstract*—A new electric split-ring resonator (ESRR) specialized for the double-sided parallel-strip line (DSPSL) is proposed. Adding a DSPSL swap to a split-ring resonator (SRR), its magnetic response becomes electrical and thus can provide negative permittivity. Such property is later applied in the design of a highly frequency-selective transmission line unit cell. The procedures are simple and it can be directly used as a compact bandpass filter with two transmission zeros on both sides of the passband.**

***Index Terms*—Double-sided parallel-strip line (DSPSL), filters, metamaterials, split-ring resonator (SRR), transmission zero.**

I. INTRODUCTION

LASTING for a decade, metamaterial-inspired technology continues growing in popularity. At microwave frequencies, the design of a variety of components, including filters, diplexers, antennas, phase shifters, couplers, and power dividers, benefits a lot from metamaterials' unusual characteristics for compactness and high performances [1]. In particular, split-ring resonators (SRRs) that provide negative permittivity or permeability play key roles in these efforts. On the basis of present printed circuit board techniques, a left-handed media can be easily realized by a transmission line loaded with these resonators. Among them, that utilized for the magnetic response is the SRR or Open SRR (OSRR), whose fundamental resonance leads to a response to the magnetic field characterized by dispersive permeability [2], [3]. By further applying Babinet's principle, Complementary SRR (CSRR) and Open CSRR (OCSRR) were introduced to design metamaterials with negative effective permittivity instead of wire arrays which are not desirable in many ways [4-6]. Another approach to obtain electrical response makes use of the electric-field-coupled resonator (ELC) with a fundamental mode that couples strongly to the electric field [7]. With these elements on hand, transmission lines with improved selectivity or wideband response have been developed [8-11]. However, in all cases, only one-sided transmission lines, such as microstrip lines (MSLs) or coplanar waveguides (CPWs), have been focused on - few literatures on their double-sided counterparts are available.

Proposed by Wheeler in 1965, the double-sided parallel-strip line (DSPSL) has not found its stage until recent years: it has been reused due to the increasing demands for multi-layered microwave integrated circuits [12], [13]. Novel DSPSL-based filters, antennas, diplexers, and couplers have been proposed [14-16]. It has some unique properties (e.g., swap structure) that can be made use of to invent special components and structures. Besides, highly frequency-selective structures for this particular transmission line are still needed, in order to further extend its applications.

Specialized for DSPSL structures, in this letter the ESRR is presented for the first time. Adding a DSPSL swap onto a SRR loop will change its resonant nature and become an ESRR. It is an electric resonator and its electrical resonant nature is analyzed using even- and odd-mode analysis, which is further proven by a symmetric resonant currents distribution. Loaded in a transmission line with a series gap, the ESRR behaves similarly with the CSRR, but CSRRs are not available in DSPSL structures as they need to be etched on the ground. Moreover, as a practical application of the ESRR, combining an ESRR and a SRR produces a highly frequency-selective line that exhibits very high-skirt selectivity even within only one unit cell.

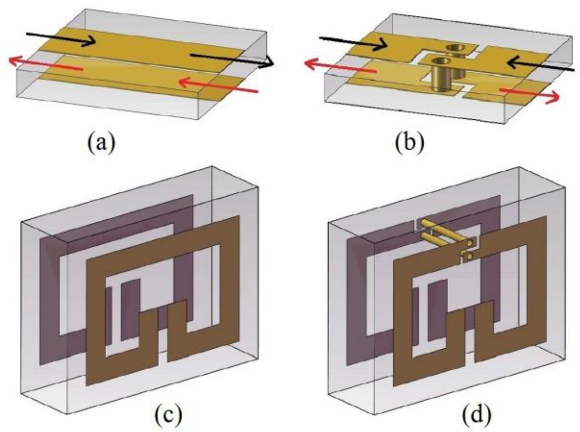

Fig. 1. Geometries of (a) a DSPSL, (b) the DSPSL swap, (c) a SRR in the DSPSL structure, and (d) an ESRR. Black and red arrows indicate the directions of currents on upper and bottom strips, respectively.

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L. Wang was with School of Electronic Engineering, University of Electronic Science and Technology of China (UESTC), Chengdu 611731, Sichuan, China. He is now with Department of Electrical and Computer Engineering, Dalhousie University, Halifax B3J 2X4, Nova Scotia, Canada. (email: luyuwang@dal.ca)

X. Q. Lin is with EHF Key Lab of Fundamental Science, University of Electronic Science and Technology of China (UESTC), Chengdu 611731, Sichuan, China (email: xianqilin@gmail.com).

II. PROPERTIES OF ESRR

As a balanced transmission line, a DSPSL consists of two identical strip lines separated by a dielectric sheet, on which signals transmit oppositely in directions (as shown in Fig. 1(a)). Between the two lines, signals are able to interchange by a DSPSL swap structure shown in Fig. 1(b), that is to say, it provides frequency independent 180° phase shift without any delay elements [16]. Fig. 1(d) depicts the proposed ESRR: it can be regarded as a SRR in the DSPSL structure (Fig. 1(c)) plus a swap in the middle. The swap splits rings of both sides equally into two, where the left part of one ring is connected to the right part of the other through a via hole, and vice versa. An ESRR can also be treated as two staggered broad-side coupled spiral resonators (BC-SRs) with one turn [17]. But the later has a magnetic fundamental respone, and is not compatible with the DSPSL (upper and bottom strips should be identical); ESRR, as will be discussed below, posseses with electrical characteristics.

Since the ESRR is symmetrical in structure, even- and odd-mode analysis is available to determine its resonant properties. As shown in Fig. 2, Y_1 and L are the characteristic admittance and length of the ESRR loop, respectively. If we ignore the distributed effects of the swap, while consider it only introduces a phase shift of π, the total electric length of the ring is $\Theta_{\text{ESRR}} = \beta L + \pi$.

For odd-mode excitation, a voltage null is created along the symmetrical plane that leads to the approximate equivalent circuit in Fig. 2(b). The resulting input admittance for odd-mode can be obtained as

$$Y_{\text{in,odd}}^{ESRR} = \frac{Y_1}{jtan(\Theta_{\text{ESRR}}/2)} \tag{1}$$

Applying the resonance condition of $Y = 0$, the odd-mode resonant frequencies can be derived as

$$f_{\text{odd}}^{ESRR} = \frac{nc}{L\sqrt{\varepsilon_{eff}}} \tag{2}$$

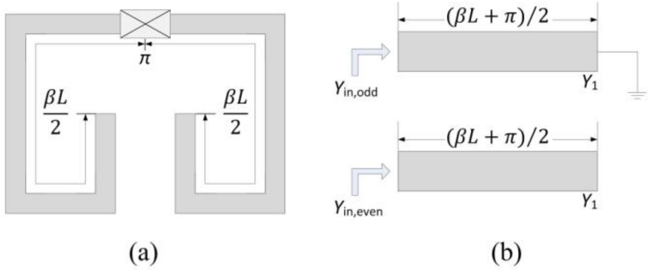
where $n = 1, 2, 3, \ldots$, c is the speed of light in free space, and ε_{eff} denotes the effective dielectric constant of the substrate.

For even-mode excitation, no current flows through the middle of the ring. Therefore we can bisect it with open circuits at the middle and then obtain the even-mode equivalent circuit in Fig. 2(b). The input admittance for even-mode can be expressed as

$$Y_{\text{in,even}}^{ESRR} = jY_1 tan(\Theta_{\text{ESRR}}/2) \tag{3}$$

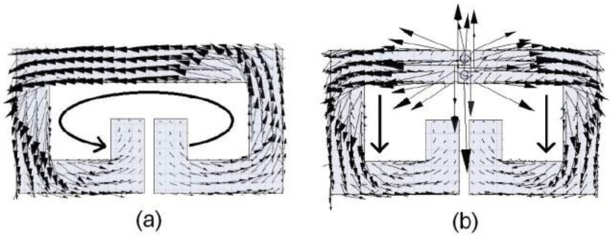
Applying the resonance condition again, the even-mode resonant frequencies is deduced as

$$f_{\text{even}}^{ESRR} = \frac{(2n-1)c}{2L\sqrt{\varepsilon_{eff}}} \tag{4}$$



(a) (b)

Fig. 2. (a) The phase shift along an ESRR; (b) odd- and even-mode equivalent circuits of the ESRR.



(a) (b)

Fig. 3. Comparison between induced currents at the fundamental resonant frequency of (a) a SRR and (b) an ESRR. In the former currents form a closed loop that is corresponding to the odd-mode, while in the later the mode is even and can be equivalent to two electric dipoles.

On the contrary, if the ring in Fig. 2(a) has no swap structure, namely, it is a SRR, the total electric length becomes $\Theta_{\text{SRR}} = \beta L$. Following the same procedures, the even- and odd-mode resonant frequencies of a SRR read

$$f_{\text{odd}}^{SRR} = \frac{(2n-1)c}{2L\sqrt{\varepsilon_{eff}}} \tag{5}$$

$$f_{\text{even}}^{SRR} = \frac{nc}{L\sqrt{\varepsilon_{eff}}} \tag{6}$$

By comparing Eqs. (2) & (4) with Eqs. (5) & (6), it can be concluded that, with a swap, the resonant modes of a SRR are changed to their opposites. This is more evident if looking directly into the induced currents on both a SRR and an ESRR at their fundamental frequencies, which have been analyzed using the full wave simulator Ansoft HFSS. On one hand, as shown in Fig. 3(a), the induced currents on a SRR form a closed loop which corresponds to the odd-mode. Based on the right-handed rule, it results in a magnetic dipole perpendicular to the dielectric sheet. On the other hand, up to ESRR (Fig. 3(b)), SRR's magnetic response is transformed into an electrical one through the swap: the surface currents distribution is bilaterally symmetric (even-mode). This case can be characterized by a pair of equivalent electric dipoles parallel to the substrate plane. This allows the ESRR to behave electrically.

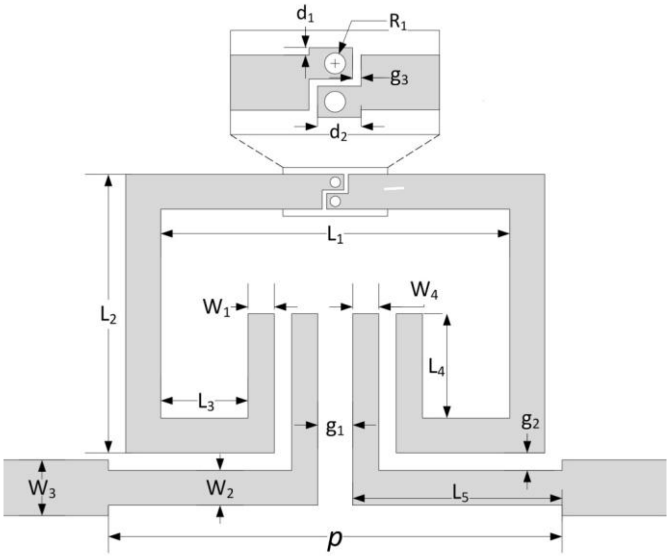


Fig. 4. Structure of the ESRR loaded DSPSL. Dimensions in millimeters are L_1 = 10, L_2 = 6.2, L_3 = 1.5, L_4 = 3, L_5 = 5.2, W_1 = 1.2, W_2 = 1.4, W_3 = 2.8, W_4 = 0.7, g_1 = 0.6, g_2 = 0.1, g_3 = 0.2, d_1 = 0.3, d_2 = 0.9, R_1 = 0.25, and p = 11. The value of W_3 is chosen to have a characteristic impedance of 50 Ω. The values of L_4, G_2, $W_{1,}$ and W_2 are selected to be narrower just to have stronger line-to-ring couplings, so as to ensure an adequate bandwidth. The swap is designed this way due to the fabrication limitations.

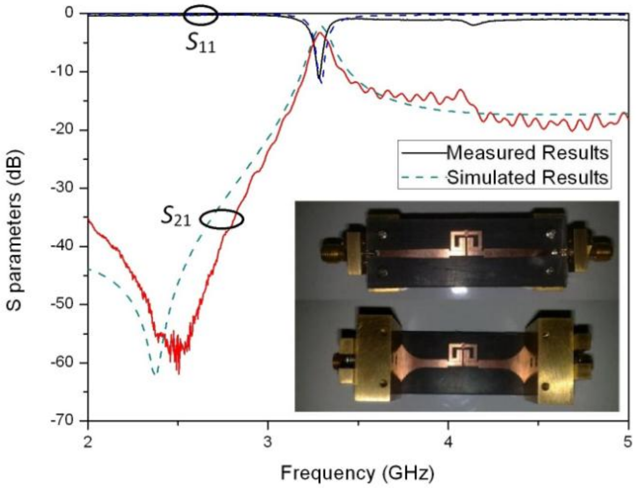


Fig. 5. Transmission (S_{21}) and reflectrion (S_{11}) coefficients for the ESRR loaded DSPSL. Insets show the upper and bottom sides of the fabricated prototype.

A planar structure schematized in Fig. 4 has been designed and fabricated on the F4B substrate (relative dielectric constant ε_r = 2.45, thickness h = 0.8 mm, and tan δ = 0.001). It consists of a proposed ESRR and a DSPSL with a series capacitance gap. In this case a fundamental resonant frequency at 3.35 GHz is needed, while with a strip width of W_1 = 1.2 mm the effective dielectric constant is ε_{eff} = 2.04 [13]. Thus from Eq. (5) the ring perimeter of the ESRR is calculated to be L = 31.4 mm. The measured and simulated S parameters are shown in Fig. 5. Excellent agreements are observed, exhibiting a passband centered at 3.3 GHz and a -60 dB transmission zero around 2.5 GHz. The experiment was carried out using Agilent E8363B vector network analyzer, for which transitions from MSLs to DSPSLs are used at both the source and load.

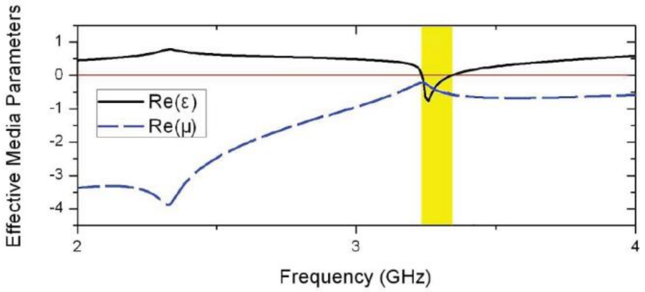


Fig. 6. Permittivity and permeability (real parts) of the ESRR loaded DSPSL. The yellow highlight indicates the double-negative band.

Note that results in Fig. 5 are similar to those of a CSRR loaded line with a series gap in [5], where there is also a transmission zero in front of the passband. In order to have a better insight, we have retrieved the effective parameters of the structure in Fig. 4 from its S parameters [18]. Fig. 6 shows real parts of its effective permittivity and permeability. The permittivity is negative in the vicinity of the resonant frequency of the ESRR, being another evidence for its electrical response. Together with the negative permeability provided by the gap discontinuity [10], this structure leads to a double-negative, namely, a left-handed passband. In general, an ESRR behaves the same electrically resonant properties with a CSRR; however, CSRRs cannot be made use of in DSPSL structures because they need to be etched on the ground – in a DSPSL there is no real ground. Therefore, ESRRs can serve as replacements in this particular situation to provide electrical responses.

III. HIGHLY SELECTIVE UNIT CELL USING ESRR

As a novel resonator, the ESRR may further find some guided-wave and radiated-wave applications. Here we propose a highly frequency-selective transmission line unit cell.

It is well studied that, with series gaps, a SRR loaded transmission line supports a forward wave propagation, where there is an transmission zero located at a higher frequency [10]: this is opposite to our ESRR loaded line that provides a left-handed passband and a transmission zero at a lower frequency. Basically, our idea is to combine those two different cases by loading a SRR and an ESRR simultaneously in a line with a series gap, so that two transmission zeros can be created.

The design procedure is simple. If the demanded bandpass frequency is given, we start with using Eq. (4) to determine the ESRR's ring perimeter. In order to get a better bandwidth, modifications of line-to-ring coupling are needed. When a structure similar with that in Section II is obtained, a SRR which has the same dimensions with the ESRR can then be loaded on the other side of the line. At last, some adjustments in dimensions are needed to get an enough insertion loss. In the case shown in Fig. 7, we fix all other dimensions (same with that in Fig. 4) and simply change the value of ESRR's L_4. When L_2 = 2.7 mm the optimized result is reached. The measurement results are shown in Fig. 8. The passband is again around 3.3 GHz, while its edges fall into two poles on both sides, and the minimum insertion loss is less than -20 dB. Compared with the CPW-based lines in [9], two transmission

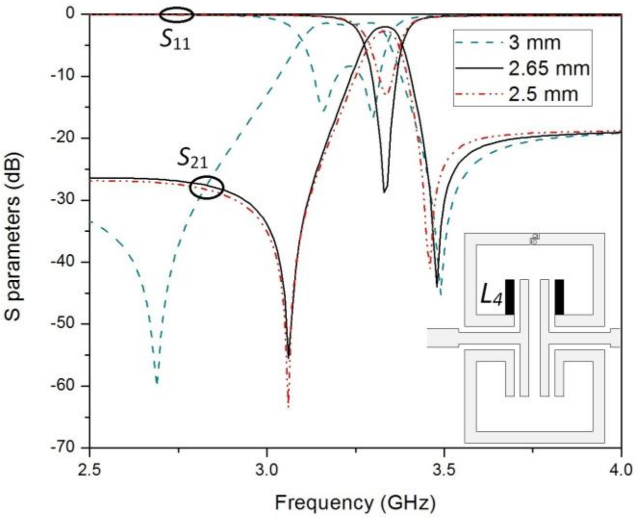


Fig. 7. Optimization of the insertion loss against L_4 though simulation.

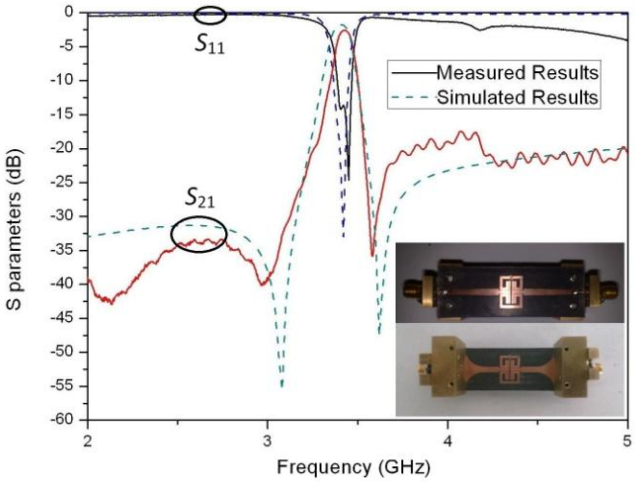


Fig. 8. Transmission (S_{21}) and reflectrion (S_{11}) coefficients of the proposed highly frequency-selective transmission line under the optimized situation. Inserts show the fabricated prototype of the proposed unit cell.

zeros in our case guarantee high-skirt selectivity within just a single unit cell. It can be used as a compact DSPSL bandpass filter directly.

IV. CONCLUSION

We present ESRR, a resonant element with electrical response other than CSRR and ELC. Its resonant characteristic has been analyzed by even- and odd-mode method as well as proven by the resonant currents distribution. Loading an ESRR in a DSPSL with a series gap, S parameters and extracted effective media parameters are studied, which again indicate its electrical resonance is similar to that of a CSRR. But CSRR is widely studied but unavailable in DSPSL structures. We further propose a highly selective transmission line unit cell by making use of ESRR's electrical properties. High skirt selectivity is observed due to a pair of transmission zeros on both sides of the passband which can be applied as a high-performance and compact filter directly. To some extent, ESRR-DSPSL-based structures are of interests in the area of designing artificial electromagnetic materials with unusual characteristics, as well as multi-layer microwave components and antennas with left-handedness and compactness.

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