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OPEN COMPLEMENTARY SPLIT RING RESONATORS: PHYSICS, MODELLING, AND ANALYSIS
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ABSTRACT: This article is focused on the physics and analysis of a new type of planar resonant particles: the open complementary split ring resonators (OCSRRs). These resonators are the complementary counterpart of the open split ring resonators (OSRRs), previously presented by some of the authors, and consist on a pair of concentric hooks etched on a metal layer in opposite orientation. Like OSRRs, OCSRRs are open resonators that can be excited by means of a voltage or current source. An accurate circuit model of the particle is proposed and experimentally validated by exciting the particle by means of a coplanar waveguide transmission line. It will be also shown that OCSRRs exhibit higher order resonance frequencies, which can be selectively suppressed by introducing additional elements, as derived from a simple analysis based on mode parity. Because of the small electrical size of OCSRRs, such particles are useful for the synthesis of planar metamaterials and microwave components. © 2010 Wiley Periodicals, Inc. Microwave Opt Technol Lett 52: 1520–1526, 2010; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.25282

Key words: metamaterials; split-ring resonator; complementary split-ring resonator; duality

1. INTRODUCTION
As the proposal of the split ring resonator (SRR) [Fig. 1(a)] as an electrically small nonmagnetic resonant particle useful for the synthesis of negative permeability media [1], and the subsequent application of this particle to the implementation of the first artificial material exhibiting left-handed wave propagation [2], there has been an intensive research activity in the field of metamaterials. Several, recently published textbooks have dealt with this hot topic [3–8]. Metamaterials are artificial structures composed with small size inclusions (or “atoms”) based on combinations of metals and dielectrics. As long as the unit cell of these structures is made small as compared with the guided wavelength, effective (or continuous) media properties arise, and their electromagnetic (or optical) behavior depend on how these unit cells are structured, rather than on their composition. Thanks to these characteristics, unusual properties can be achieved, including left-handed wave propagation, super-resolution, negative refractive index, or cloaking, among others.

There are several approaches for the synthesis of metamaterials. One of these approaches is based on the use of resonant particles like the SRR, or other electrically small resonators (spiral resonators [9–11], broad-side coupled SRRs [12], chiral resonators [13], or other resonant structures with more complex topology [14]). These resonant elements have been used for the synthesis of bulk 1D, 2D, and 3D metamaterials, and also for the synthesis of planar metamaterial structures, such as frequency selective surfaces [15] or metamaterial transmission lines [16]. In 2004, it was presented the complementary split ring resonator (CSRR) [17], which has been demonstrated to be a very interesting particle for the implementation of composite right/left-handed transmission lines in microstrip technology. The CSRR is the complementary counterpart of the SRR, and hence it consists on a pair of slot rings with apertures in opposite orientation, etched on a metallic screen [Fig. 1(b)]. The CSRR can be excited by means of an axial time varying electric field, and, etched in the ground plane of a microstrip line, it provides a negative effective permittivity to the structure, as has been previously discussed [17, 18] (other topologies inspired on the CSRR topology have also been used for the synthesis of one-dimensional negative permeability media [19]).

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This article is focused on a novel resonator, which is the missing particle in the list of Figure 1: the open complementary split ring resonator (OCSRR). Section 2 is devoted to the modeling of this particle; in Section 3, this model is validated through experiment; in Section 4, we discuss the deviations from the prediction of the OCSRR model at high-frequencies; finally, prospective applications and the main conclusions are highlighted in Section 5 and 6, respectively.

2. CIRCUIT MODEL OF THE OCSRR

The OCSRR is obtained from the SRR topology by opening it (as in the OSRR) and applying duality (as in the CSRR). It is thus the complementary counterpart of the OSRR, and for this reason it has been called OCSRR (see a typical layout in Fig. 2). However, the term “open” in the nomenclature of this particle must be considered with some caution. “Open resonator” means that the particle exhibits two metallic terminals for excitation (through a voltage or current source), as opposed to closed particles, where these terminals are absent, and the particle is magnetically or electrically excited. Thus the nomenclature of the OSRR is very clear on account of its topology [the metallic terminals ports are indicated in Fig. 1(c)]. In the case of the OCSRR, what does the term “open” mean? In other words: where are the metallic connecting terminals? Such terminals are the metal regions below and above the particle, as indicated in Figure 2. Between the upper and lower terminals, there is an electric short through the metal between the inner and outer slot rings forming the particle, but there is also capacitive connection through the capacitances across the slots. Thus, according to this, the circuit model of the particle is an open parallel resonant tank, as Figure 2(b) illustrates. Indeed, from the previous analysis on SRRs [21], OSRRs [22], and CSRRs [20] (summarized in Section 1), it follows that the inductance is \(L_o\), that is, the inductance of the metallic strip between the ring slots, and the capacitance is \(C_c\), that is the same as the capacitance of the CSRR. Therefore, it is expected that the resonance frequency of the OCSRR is half the resonance frequency of the CSRR, although in practice some deviation is expected because of the presence of the metallic regions between the inner metal of the slot rings and the lower electrode. Obviously, the model of the OCSRR is valid in a limited range of the spectrum (as occurs in SRRs, CSRR, etc). This aspect will be discussed in Section 4. Concerning the calculation of \(L_o\), this electrical parameter is given by the inductance of the central strip of the OCSRR surrounded by the inner and outer metal of the particle, as if these metallic regions were the ground planes of a circular CPW structure. Thus, \(L_o\) can be calculated from well know formulas giving the per-unit length inductance of a CPW structure without backside metal [23]. \(C_c\) can be obtained from a variational method reported in [20].

3. VALIDATION OF THE MODEL AND RESULTS

To experimentally determine the resonance frequency of the OCSRR, the particle can be excited by using a coplanar waveguide (CPW) configuration. The topology of the test structure is shown in Figure 3. Two symmetrically placed OCSRRs have been etched in the slots of the CPW. To avoid the excitation of parasitic modes (slot mode) the different ground-plane regions have been connected through vias and metallic strips etched in the back side of the substrate, as depicted in Figure 3.

According to the OCSRR model presented in Section 2, the test structure can be modeled by cascading a pair of shunt resonant tanks between two transmission lines (the latter modeling the CPW sections of the structure), as Figure 3(b) illustrates. By designing the host CPW with a characteristic impedance of \(Z_0 = 50 \, \Omega\), the transmission coefficient between the input and the output port must be maximum at the resonance frequency of the OCSRR (provided that the impedance of the ports is also 50 \(\Omega\), as usual). The reason is that the shunt branch opens at this frequency, and the injected power must be totally transmitted to the load (except certain power that may be lost because of the...
The substrate used is RO3010 with a dielectric constant of 10.2. The host CPW has a slot and central strip widths of $G = 1$ mm and $W = 3.64$ mm, respectively. The length of the structure is 10.4 mm (excluding access lines). The dimensions of the OCSRRs are, in reference to Figure 2, $c = 0.6$ mm, $d = 0.6$ mm, and $e_{\text{cs}} = 5$ mm. The structure has been implemented on the Rogers RO3010 substrate with a dielectric constant $\varepsilon_r = 10.2$, dielectric thickness $h = 1.27$ mm (metal thickness $t = 35$ $\mu$m). The vias (connecting the upper and lower metallic layers) and the back substrate side metallization are indicated in black. The backside metal consists thus on a rectangle with a strip width of 0.2 mm.

The simulated (by using the Agilent Momentum electromagnetic software) and measured (by using the Agilent 8720ET vector network analyzer) frequency responses of the test structure shown in Figure 3 are depicted in Figure 4(a). For the measurement, the standard Open/Short/Load/Through calibration technique employing the Agilent 85052D calibration kit has been applied. It is also depicted in this figure the circuit simulation that has been obtained by extracting the parameters of the LC resonant tank. Losses have been excluded and the parameters have been inferred from the electromagnetic simulation by curve fitting.

The resonance frequency of CSRRs and OCSRRs can be determined from the simulated (by means of electromagnetic solvers) or measured transmission, $S_{21}$, or reflection, $S_{11}$, coefficients of the test structure.

The simulated (by using the Agilent Momentum electromagnetic software) and measured (by using the Agilent 8720ET vector network analyzer) frequency responses of the test structure shown in Figure 3 are depicted in Figure 4(a). For the measurement, the standard Open/Short/Load/Through calibration technique employing the Agilent 85052D calibration kit has been applied. It is also depicted in this figure the circuit simulation that has been obtained by extracting the parameters of the LC resonant tank. Losses have been excluded and the parameters have been inferred from the electromagnetic simulation by curve fitting.

Figure 4 Simulated and measured transmission ($S_{21}$) and reflection ($S_{11}$) coefficients for the structure shown in Figure 3(a), and a microstrip line loaded with a CSRR (b). In both cases a 50 $\Omega$ host line has been considered, and the resonators are identical. The circuit simulations obtained by extracting the circuit elements from the electromagnetic simulation are also depicted. Note that the resonance frequency of the CSRR is neither given by the notch in the reflection coefficient. Thus we have only one degree of freedom and the determination of the inductance and capacitance of the CSRR from curve fitting is straightforward. The circuit simulation is in good agreement with the electromagnetic simulation and measurement. We have also obtained the resonance frequency of a CSRR with identical dimensions, that has been etched in the ground plane of a microstrip line implemented on the same substrate, that is, the Rogers RO3010 with a dielectric constant $\varepsilon_r = 10.2$, dielectric thickness $h = 1.27$ mm and metal thickness $t = 35$ $\mu$m [Fig. 4(b)]. The resonance frequency of the CSRR has been inferred according to the method reported in [24], where it is also indicated the configuration of the structure. For the OCSRR, the resonance frequency obtained from measurement and simulation are, $f_{0}^{\text{exp}} = 0.95$ GHz and $f_{0}^{\text{sim}} = 1.01$ GHz, respectively, and the extracted inductance and capacitance of the particle are $L = 10.41$ nH and $C = 2.33$ pF. For the CSRR, $f_{0}^{\text{exp}} = 1.96$ GHz, $f_{0}^{\text{sim}} = 2.014$ GHz, $L = 2.28$ nH, and $C = 2.74$ pF. These results are in agreement with the model of the CSRR from which it follows that the resonance frequency of this particle is half the resonance frequency of the CSRR (with identical dimensions), the capacitances are very similar, and the ratio of inductances is close to 4.

We have considered additional OCSRRs and CSRRs with different radius and $c = d = 0.2$ mm, and we have determined the resonance frequency for all of them. The results (Table 1) show that by increasing the radius of the particles, the ratio between the resonance frequency of the CSRR and the OCSRR is closer to two. This is an expected result as the effect of the inter-metallic region between the central strip and the metal inside the OCSRR vanishes for sufficiently large particles. Note also that for the first row ($e_{\text{cs}} = 7$ mm), the ratios between the resonance frequencies and the reactive parameters of the particles are very close to the theoretical values. We have also analyzed the effects of varying $c$ and $d$, leaving unaltered the external radius of the particle. The results are depicted in Table 2. It is also clear according to this table that as $c$ and $d$ decrease, the model predictions are more accurate.

The results shown in this section validate the reported model of the new proposed particle. In the vicinity of the resonance frequency of the OCSRR, the particle is accurately described by...
TABLE 1 Resonance Frequency for the OCSRR and CSRR with the Indicated External Radius

<table>
<thead>
<tr>
<th>$r_{ext}$ (mm)</th>
<th>$f_{OCSRR}$ (GHz)</th>
<th>$C_{OCSRR}$ (pF)</th>
<th>$L_{OCSRR}$ (nH)</th>
<th>$f_{CSRR}$ (GHz)</th>
<th>$C_{CSRR}$ (pF)</th>
<th>$L_{CSRR}$ (nH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.54</td>
<td>4.92</td>
<td>18.28</td>
<td>1.07</td>
<td>4.92</td>
<td>4.50</td>
</tr>
<tr>
<td>5</td>
<td>0.78</td>
<td>3.41</td>
<td>12.21</td>
<td>1.55</td>
<td>3.68</td>
<td>2.87</td>
</tr>
<tr>
<td>3</td>
<td>1.33</td>
<td>2.08</td>
<td>7.05</td>
<td>2.75</td>
<td>2.84</td>
<td>1.18</td>
</tr>
</tbody>
</table>

In all the cases $c = 0.2 \text{ mm}$ and $d = 0.2 \text{ mm}$.

means of an open-parallel resonant tank, with an inductance four times larger than that of the CSRR, and identical capacitance. In the next section, deviations from the predictions of the model at higher frequencies are analyzed and discussed.

4. DISCUSSION

The description of the OCSRR (and the other related particles such as the SRR, CSRR, and OSRR) by means of a simple lumped element model is restricted to a limited range of frequencies. The reason is that at high frequencies, the particles are not electrically small. In general, for metamaterial and circuit design, a proper description of the particles in the vicinity of their first resonance suffices. However, some deviations from the predictions of the model at moderate frequencies are present, and it is of interest to analyze their origin. This is the main aim of this section. In Figure 5, we depict the frequency response of the structure shown in Figure 3(a), inferred from electromagnetic simulation, and also the circuit simulation that has been inferred from the circuit of Figure 3(b) with the extracted parameters of the OCSRR. The frequency range has been extended to roughly five times the first resonance frequency of the OCSRR, to clearly appreciate the moderate to high frequency effects. As in Figure 4, there is a deep notch in the transmission coefficient (transmission zero), located at 2.86 GHz, preceded by a very narrow spike (at 2.42 GHz). These effects are not predicted by the model of Figure 3(b). The transmission zero present at 2.86 GHz is related to the fact that the metallic region present between the central strip of the CPW, and the inner metallic region of the OCSRR introduces an extra inductance to the model. This inductance does not appreciably affect the frequency response in the vicinity of the resonance frequency of the OCSRR (at roughly 1 GHz), but is responsible for the transmission zero present at a higher frequency. Such transmission zero can be accounted for by introducing an additional inductance to the model, as depicted in Figure 6(a). At the frequency where the shunt branch shorts, namely:

$$f_s = \frac{1}{2\pi \sqrt{\frac{L_i + L_o}{L_i C_i L_o}}}$$  \hspace{1cm} (1)

signal propagation is precluded, and the injected power is reflected back to the source (transmission zero frequency). By

TABLE 2 Resonance Frequency for the OCSRR and CSRR with the Indicated Values of $c$ and $d$

<table>
<thead>
<tr>
<th>$c = d$ (mm)</th>
<th>$f_{OCSRR}$ (GHz)</th>
<th>$C_{OCSRR}$ (pF)</th>
<th>$L_{OCSRR}$ (nH)</th>
<th>$f_{CSRR}$ (GHz)</th>
<th>$C_{CSRR}$ (pF)</th>
<th>$L_{CSRR}$ (nH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.58</td>
<td>4.14</td>
<td>17.36</td>
<td>1.16</td>
<td>4.09</td>
<td>4.64</td>
</tr>
<tr>
<td>0.4</td>
<td>0.65</td>
<td>3.69</td>
<td>16.72</td>
<td>1.23</td>
<td>3.98</td>
<td>4.23</td>
</tr>
<tr>
<td>0.5</td>
<td>0.69</td>
<td>3.42</td>
<td>15.72</td>
<td>1.30</td>
<td>3.62</td>
<td>4.22</td>
</tr>
<tr>
<td>0.6</td>
<td>0.74</td>
<td>3.14</td>
<td>15.02</td>
<td>1.35</td>
<td>3.44</td>
<td>4.04</td>
</tr>
</tbody>
</table>

In all cases $r_{ext} = 7 \text{ mm}$.

Figure 5 Electromagnetic simulation (transmission and reflection coefficients) of the structure shown in Figure 3(a). In the figure are also included the transmission and reflection coefficients obtained from the circuit model of Figure 3(b) (with extracted parameters), the circuit model of Figure 3(b) with an additional inductance to take into account the transmission zero (Fig. 6(a)), and the circuit of Figure 3(b) with an additional resonant element to account for the third resonance of the OCSRR (Fig. 6(b)). The elements values are: $L_i = 10.41 \text{ nH}$, $C_i = 2.33 \text{ pF}$, $L_o = 1.53 \text{ nH}$, $L_e = 0.69 \text{ nH}$, and $C_e = 2.45 \text{ pF}$. The first, $f_1$, second, $f_2$, and third, $f_3$, resonance frequencies of the OCSRR, and the transmission zero frequency, $f_s$, of the structure, are indicated.

Taking into account the effects of such inductance, the transmission zero frequency is predicted by the circuit model, as shown in Figure 5.

The spike present at 2.42 GHz is because of the second resonance frequency of the OCSRR, but its effects are difficult to model in practice. At roughly 3.83 GHz, there is an additional transmission band, which is related to the third resonance frequency of the OCSRR, and can be accounted for by the model simply by introducing an additional resonator, as shown in Figure 6(b). The inductance and capacitance of this new resonator can be determined from the electromagnetic simulation of the structure as for the resonator describing the first resonance frequency of the OCSRR. The circuit simulation of the complete model is also depicted in Figure 5. Except by the spike preceding the transmission zero, the frequency response obtained from circuit simulation is in good agreement with the electromagnetic simulation.

To get more insight on the characteristics of the OCSRR-loaded CPW transmission lines, we have modified the width and length of the metallic region present between the central strip of the CPW and the inner metallic region of the OCSRR. By doing

Figure 6 Improved circuit models of the CPW structure loaded with a pair of OCSRR to take into account the transmission zero (a) and the transmission zero and third resonance of the OCSRR (b)
this, we modify the inductance series connected to the resonant tank modeling the OCSRR, with the result of a shift in the transmission zero frequency. This has been corroborated from the electromagnetic simulation of the structure with different dimensions, length \( D \) and width \( X \), for the above cited metallic region (Fig. 7). Note that dimensions of the structure in Figure 7 is different than those of Figure 3.

We have also obtained the magnetic currents, provided by the Agilent Momentum commercial software, obtained at the relevant frequencies of the structure in Figure 3 (Fig. 8). At 1.02 GHz, the first resonance frequency of the OCSRR, the magnetic currents at both rings forming the OCSRR are codirectional. This means that the excited mode of the OCSRR is an odd mode, which can be interpreted as a slot mode of the CPW structure constituted by the inter-rings region of the slot rings and the surrounding metallic regions. This corroborates the relation with the OSRR [22] when the Babinet principle is applied, just as in the SRR and the CSRR [18]. Note that the maximum current (only one current maximum appears) takes place in the region between the rings and the central strip of the CPW. This is coherent with the maximum magnetic current at the first resonance frequency of a complementary spiral resonator (CSR), not shown, which takes place in the region connecting the inner and outer loop of the spiral, also note that in the region between the rings and the central strip of the CPW the magnetic currents are contradirectional. Thus, in this region, the mode is even.

At 2.42 GHz, where the spike appears, the magnetic currents in the rings are contradirectional, although the inner ring is scarcely excited. In the interconnecting region between the rings and the central strip of the CPW, the currents are codirectional, which means that in this region the mode is odd. With the presence of the connecting strip (and vias) in the bottom side of the structure, this mode is minimized, and this explains that the inner ring is scarcely excited. As can be seen in the current diagrams, at this frequency, power is not transmitted to the right-hand side of the structure, and hence it is reflected back to the source, giving a notch in transmission.

Finally, at 3.83 GHz (the third resonance frequency of the OCSRR), the magnetic currents in the rings exhibit three maxima: one in the external ring, another one in the internal ring, and the third one in the region between the rings and the central strip of the CPW. As occurs at the third resonance of the CSR, in the region where the current of one ring maximizes, the other ring exhibits nearly zero current. Nevertheless, as at the first resonance, the magnetic currents in the region between the rings

![Figure 7](image7.png) Test structure for the determination of the effects of varying the dimensions of the metallic region present between the central strip of the CPW and the inner metallic region of the OCSRR (a) and simulated responses with several lengths, \( D \), (b) and widths, \( X \), (c). The host CPW has a slot and central strip widths of \( G = 1 \) mm and \( W = 3.64 \) mm, respectively. The length of the structure is 14.4 mm. The dimensions of the OCSSRs are, in reference to Figure 2, \( c = 0.4 \) mm, \( d = 0.4 \) mm, \( r_{ext} = 7 \) mm, \( X = 1.6 \) mm in (b), and \( D = 3.7 \) mm in (c). For the substrate, the dielectric constant \( \varepsilon_r = 10.2 \) and thickness \( h = 1.27 \) mm

![Figure 8](image8.png) Magnetic current diagrams of the OCSRR obtained at the relevant frequencies of Figure 5. Given that the structure is symmetric, half of the structure has been represented. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

![Figure 9](image9.png) OCSRR with metallic strips connecting the outer and inner metallic region to suppress the first and third resonances (a), and simulated frequency response (b)

![Figure 10](image10.png) Strategy to suppress the second resonance of the OCSRR with only one metallic strip (a), adding a thin strip (b), and adding a wide strip (c)
and the CPW are contradirectional, which means that in this region, the mode is even.

The parity of the different modes suggests that it is possible to selectively cancel them. The first resonance frequency can be merely cancelled by connecting the inner and outer metallic region of the OCSRR, by means of metallic strips etched in the back substrate side and metallic vias, as Figure 9 illustrates (note that in Fig. 9, the simulated structure is that of Fig. 7). Indeed, the third resonance frequency is also partially cancelled by introducing such additional elements [Fig. 9(b)]. Further cancellation of the second resonance is achieved by connecting the metallic parts present at both sides of the slots in the region between the CPW and the OCSRR (access region), as illustrated in Figure 10. The reason is that the access region exhibits an odd mode at this frequency, as has been explained before. Thus, through electric connection of the external metallic regions, the mode is partially suppressed. This also prevents the slot mode of the CPW structure at the first resonance of the OCSRR (the resonance frequency of interest). For this reason, we are forced to use this electrical connection by introducing the back side metallic strip and vias. This is effective in suppressing the slot mode of the CPW structure. However, it has been found that to substantially suppress the second resonance frequency of the OCSRR, it is necessary to introduce several strips in parallel or, alternatively, a wide strip. The responses with several strips are illustrated in Figure 11, where it can be seen that the spike is practically suppressed. Obviously, it is possible to effectively and simultaneously suppress the second and third resonance by combining the two proposed strategies.

To summarize this discussion, it has been found that the phenomenology associated to OCSRRs coupled to CPW structures is very rich, with the presence of several resonances that can be selectively suppressed by the addition of additional elements (backside metallic strips and vias). The suppression of higher order resonances is of interest to improve the wideband behavior of microwave components on the basis of these resonant elements (for instance in filters).

5. POTENTIAL APPLICATIONS

Although this article is mainly focused on the physics and modeling of OCSRRs, we would like to highlight that, because of the small electrical size of OCSRRs (at the first resonance frequency), these particles may find applications in the design of microwave circuits where size reduction is mandatory. Such particles are open, parallel resonators that can be applied to the design of microwave filters [25] and diplexers, among other microwave components. They are also of interest for the design of metamaterial transmission lines. Specifically, OCSRRs can be combined with OSRRs to implement composite right/left-handed transmission lines [26] in CPW (as has been already demonstrated by the authors [27]) or in microstrip technology. The potential of these artificial lines is very high as they are small and allow for further design flexibility, as compared with conventional lines, through dispersion and impedance engineering. Such lines are being applied at present by the authors to the design of microwave filters and dual band components based on metamaterial concepts.

6. CONCLUSIONS

In conclusion, it has been shown that OCSRRs are electrically small, open, and parallel resonators that can be modeled by means of a parallel resonant tank where the elements are closely related to those of the CSRR. We have presented the circuit model of a CPW structure loaded with a pair of OCSRRs, and the model has been validated through simulation and
experiment. It has been found that a transmission zero arises at higher frequencies. The origin of this transmission zero has been interpreted and accounted for in the model by introducing an extra inductance. We have also shown that OCSRRs exhibit higher order resonance frequencies, that correspond to even or odd modes of OCSRR excitation. From this analysis, we have inferred the strategy for resonance suppression (by means of properly allocated metallic strip and vias connecting the different ground plane regions), which has been validated through electromagnetic simulation. Finally, we have highlighted prospective applications of OCSRRs in microwave engineering. OCSRRs are the open version of CSRRs, in the same form that OSRRs are the open version of SRRs. With this new particle, we enhance the design capabilities of microwave circuits and metamaterial-inspired structures on the basis of resonant elements.

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ON THE EFFECTS OF RESONATOR’S ELECTRICAL SIZE ON BANDWIDTH IN RESONANT-TYPE METAMATERIAL TRANSMISSION LINES

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ABSTRACT: In this article, an analysis of resonant type metamaterial transmission lines is carried out. Specifically, the effects of the dimensions and resonator characteristics on the frequency response are studied and interpreted to the light of the equivalent circuit model of the lines based on split ring resonators and complementary split ring resonators. In this work, the duality between both kinds of lines can also be observed. This study is important for the application of these artificial lines to microwave circuit design, because important guidelines concerning device bandwidth can be inferred. © 2010 Wiley Periodicals, Inc. Microwave Opt Technol Lett 52: 1526–1530, 2010; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.25232

Key words: metamaterials; left-handed transmission lines; electromagnetic resonators; device miniaturization