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DUPLEXERS AND MULTIPLEXERS BASED ON MICROSTRIP LINE LOADED WITH COMPLEMENTARY SPLIT RING RESONATORS

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Abstract—On the basis of backward coupling and left-handed microstrip line, new designs of duplexers and multiplexers will be presented and tested in different configurations. By using microstrip lines with Complementary Split Ring Resonators (CSRRs) etched on the ground plane along with series capacitive gaps in the upper conductor, forward coupling will be inverted into backward coupling. Compact size and fully planar fabrication techniques are important characteristics in the devices proposed.

1. INTRODUCTION

The study of the *Split Ring Resonator*, (SRR) proposed by Pendry [1] has been of great scientific interest in the last years. Following the SRR, the *Complementary Split Ring Resonator* (CSRR) particle, i.e., the SRR etched in a metallic plane or in a metallic transmission line was presented by some of the authors [2]. The particle CSRR possesses properties complementary to the SRR, it can be excited by an electric field axial to the ring [3] and it can be also excited by a magnetic field in the plane of the ring and perpendicular to the slits by the bianisotropy property of the CSRR [4]. In a microstrip line the CSRR can be properly excited if it is placed in the ground plane under the conductor strip, since in a microstrip line the electric field is mainly confined between the conductor strip and the ground plane. When a CSRR is properly excited, a negative electric permittivity media is produced in the vicinity of the quasi-static resonant frequency. By

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combining CSRRs with a negative magnetic permeability media it could be obtained a simultaneously negative magnetic permeability and electric permittivity media with the properties described by Veselago for these Left-Handed Materials (LHM) [5]. The negative effective permeability is obtained by adding series capacitive gaps along the microstrip line as it can be seen in Fig. 1 [6]. Near the quasi-static resonant frequency these media behave as a LHM as it has been demonstrated in [6], and it can be seen in the negative slope of the dispersion diagram of the unit cell in Fig. 1(b).

On the other hand, in the studies about couplers performed by Ikäläinen and Matthaei [7] it was demonstrated that in a coupler made of two conventional microstrip lines smoothly approaching each other, forward coupling is produced by the difference in the phase constants of the even and odd modes instead the backward coupling produced in conventional $\lambda/4$ parallel coupled lines produced by the difference in the impedances of the even and odd modes.

Based on forward couplers and using LHM like the one shown in Fig. 1, *backward couplers* [8] have been presented, based on the property of antiparallelism between energy and phase propagations in this kind of media with simultaneously negative permittivity and permeability, inverting the energy propagation in the coupled line. A theoretical study for coupled-line couplers in left-handed media is available in [9].

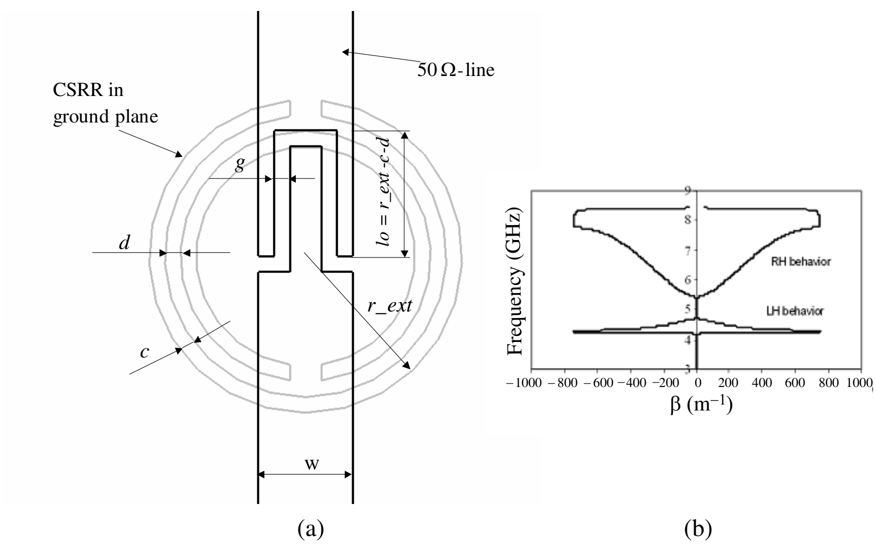
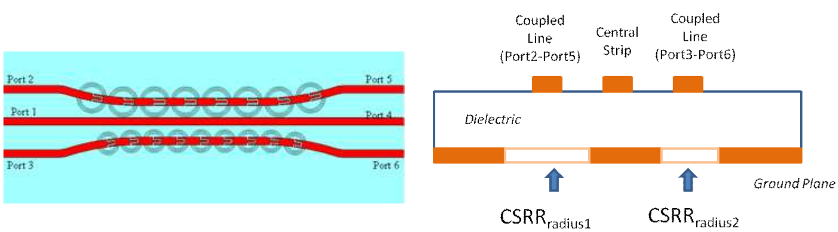


Figure 1. (a) Layout of LHM cell with CSRR etched in the ground plane and capacitive gap in microstrip line. (b) Dispersion diagram.

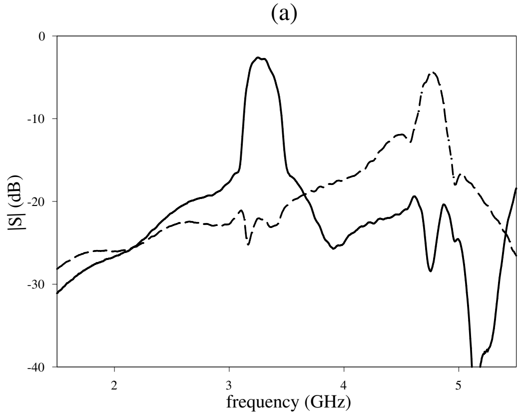
Other devices using the CSRR particle have been proposed recently [10, 11], even a duplexer based on a LHM has been presented [12]. In this letter the design techniques for duplexers and multiplexers in left-handed microstrip line and based on backward coupling phenomena are presented. Measured and simulation results will be shown and discussed. Moreover improvement performance in bandwidth and compactness will be demonstrated.

2. DUPLEXERS

The layout of the duplexer proposed is depicted in Fig. 2. It consists in one microstrip line and another microstrip line parallel-coupled to the initial one and loaded with CSRR elements, which are placed side by side one to the other. The CSRR dimensions have been tuned following the design procedure described in [13]. Each one of the CSRR elements are coupled to the respective microstrip transmission line, with an equivalent circuit model which is depicted in Fig. 3. Coupling between



(a)



(b)

Figure 2. (a) 6-port duplexer, top view and transversal view of the device. (b) Frequency response: S_{31} solid line, S_{41} dashed line.

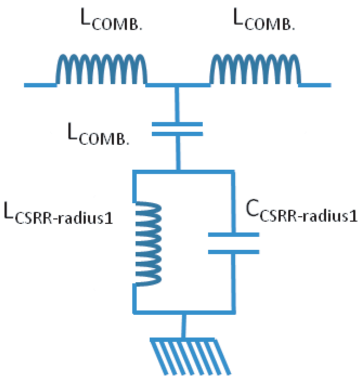


Figure 3. Equivalent circuit representation for each CSRR element coupled to a microstrip transmission line. In the case of duplexer design, two different radius values for the CSRR elements are employed, due to the fact that two different frequency bands are present.

elements is given by inductive as well as capacitive relations (given in both cases by edge coupling of the CSRR borders etched within the ground planes), which are embedded within the L and C values of the equivalent circuit models. The quasi-static resonance frequency is given in essence by the LC tank, under excitation (due to application of Babinets principle) of axial electric field lines [2] and modified by capacitive coupling to the transmission line, a microstrip line of finite thickness [13]. The behavior of the combined conventional/CSRR loaded microstrip lines can be described by the classical coupled line model decomposition of even and odd mode [14]. The progressive nature of coupling is similar to conventional backward couplers, only modified locally due to the excitation of the quasis-static resonance, as previously stated in [8].The enhancement of backward coupling is due to the fact that in the region of operation of the device, the line loaded with CSRR elements exhibits a negative value of the propagation constant, as can be seen from the dispersion diagram depicted in Fig. 2. Therefore, in a simplified manner, the design on the complete device requires the desired frequency of operation, which will determine the dimensions of the CSRR elements, which will then be embedded in the final model. It is worth noting that due to the strong dependence with axial electric field excitation and the resonant behavior of the equivalent quasi-static circuit, the CSRR elements embedded within the microstrip line will not perturbate the overall response of the device in out-of-band operation.

The CSRRs in the upper line (from port 3 to port 5) have an external radius $r_{ext1} = 2.4\,\text{mm}$, strip width $c = 0.2\,\text{mm}$ with a separation between the inner and the outer ring $d = 0.2\,\text{mm}$ (the last two parameters will be the same for all the rings in this work). The capacitive gap have a slot width $g = 0.2\,\text{mm}$ and is the same for all gaps in the article and the gap length depends on the external radius and it can be calculated from $lo = r_{ext} - c - d$ that for the gaps in upper line gives $lo = 2\,\text{mm}$. The CSRRs in the lower line (from port 4 to port 6) have an external radius $r_{ext2} = 1.8\,\text{mm}$. In this case the upper line is composed of 8-LHM cells and the lower line has 9-LHM cells, both parallel coupled lines are smoothly approached to the central line. The small interline distance is $s = 1.8\,\text{mm}$ that in a conventional $\lambda/4$ parallel-lines coupler provides a coupling level lower than 20 dB. Simulations were made using the Agilent$^{\text{TM}}$ *ADS Momentum* and *CST Microwave Studio*$^{\text{TM}}$. The substrate employed is *Rogers* RO3010 with dielectric constant $\varepsilon_r = 10.2$, height $h = 1.27\,\text{mm}$ and metal thickness $t = 35\,\mu\text{m}$. The prototype in Fig. 2 was fabricated by means of standard photo/mask etching technique and it has been measured in an *Agilent-8722* network analyzer. Fig. 2 shows the measured frequency response of the proposed device.

Backward power coupling, around -3 dB at 3.6 GHz in S_{31} and -4 dB at 4.8 GHz in S_{41} is achieved, which are much better than conventional $\lambda/4$ parallel-lines coupler mentioned before. Insertion losses are due to conductor and dielectric losses. As it can be seen, more than 20 dB of isolation between ports is obtained.

3. FOUR PORT MULTIPLEXER

Following the same design technique employed in previous sections a 4-output multiplexer is presented, as an extension of the duplexer design previously presented. The basic condition to achieve successful operation is to have enough surface in the ground plane where the CSRR elements will be embedded. Due to the fact that excitation is mainly given by the normal component of the electric field, CSRR elements in an optimal design must be placed just underneath the microstrip line [2]. The layout of the device is shown in Fig. 4. It consists of one input central microstrip line and four similar output stages. Each output stage is composed of one LHM parallel coupled line with 3 CSRR based-cells tuned to the frequency selected. In the stage of port 6 an additional cell has been included due to the smaller dimensions of the CSRR particles, which allow for this additional inclusion. The dimensions for the device in Fig. 3 are, $r_{ext1} = 2.4\,\text{mm}$, $r_{ext2} = 2.2\,\text{mm}$, $r_{ext3} = 2\,\text{mm}$ and $r_{ext4} = 1.8\,\text{mm}$, which are chosen in

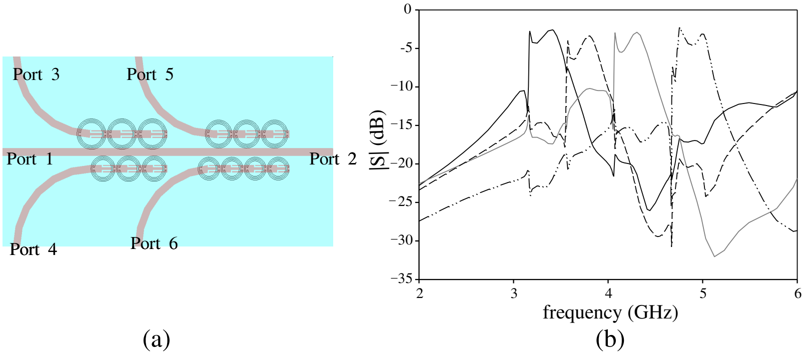


Figure 4. (a) Layout of the 4-output duplexer. (b) Frequency response: S_{31} solid black line, S_{41} dashed line, S_{51} solid grey line, S_{61} dash-dotted line.

order to obtain quasi-static resonance of the CSRR elements embedded in the microstrip line [2, 13]. Separation between parallel coupled lines and the central line is $s = 1.5\,\text{mm}$.

In Fig. 3 the frequency response of the multiplexer proposed is depicted. The passband tuned at the frequency selected for each cell is achieved in each output.

The frequency selectivity obtained allows this device to operate as a multiplexer in transmission or as a filter bench in reception. Moreover the coupling length of the CSRR loaded microstrip line section for the output ports is lower than 16 mm which is smaller than $\lambda/4$ for each frequency. The number of bands can be increased by adding new outputs tuned to the desired frequencies, by giving the CSRR elements in each one of the ports the adequate dimensions to achieve quasi-static resonance [2, 13].

4. CONCLUSIONS

Duplexers and multiplexers with great frequency selectivity have been synthesized by inverting forward coupling into backward coupling by using a microstrip line with left-handed behavior. The design of the devices is based on the identification of the different frequencies of operation, which are made coincident with the quasi-static resonance frequency of the CSRR elements which are embedded within the coupled microstrip lines. Fully planar design and compact size are important features in the devices presented. Moreover the availability of selecting different frequencies in many configurations provides an advantage of these devices in actual multi-band applications.

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