IASET: Journal of Electrical and Electronics Engineering (IASET: JEEE)
ISSN(P): Applied; ISSN(E): Applied
Vol. 1, Issue 1, Jan - Jun 2016; 11-16

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

DIRECTIONAL COUPLER BASED ON METAMATERIAL SQUARE CSRR SHAPE

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ABSTRACT

Metamaterials are artificial structures that can be designed to exhibit specific electromagnetic properties that are not in the nature. In this paper, we design a directional coupler, based on the theory of the split-ring resonators (SRRs), and the complementary SRR (CSRRs). The simulations of the directional coupler are based on the SRR and CSRR square structures. The advantage of this circuit is that the area of the coupling is great as regards to the coupler based on the circular structures of the SRR and CSRR. The results of simulation with the miniature structures show the backward-wave phenomenon of the left-handed (LH) material.

KEYWORDS: Directional Coupler, Metamaterial SRR and CSRR, Square Shape, Backward Waves

INTRODUCTION

Metamaterial transmission lines are one-dimensional propagating structures consisting on a host line loaded with reactive elements. References [1, 2] give a wide overview on this topic. The most outstanding property of these artificial lines is the controllability of their electrical characteristics (impedance and phase), which are superior to that of conventional lines due to the presence of loading elements. This allows us for the synthesis of artificial lines with extreme impedances and/or artificial lines where the electrical length is not directly related to the physical length (as occurs in conventional lines). This latter characteristic is a consequence of the controllable dispersion diagram of such lines, and it has a fundamental implication: the required electrical lengths of the lines (which are determined by the specific applications) are achievable with structures whose dimensions are significantly smaller than those dimensions that result when using conventional lines. In many applications, the required phase shift (and impedance) of the lines can be satisfied by means of a single stage structure [3], this being the optimum solution for device miniaturization. At this point, we would like to mention that although the commonly accepted definition of metamaterial transmission line refers to an effectively homogeneous periodic structure. The reason is that for microwave circuit design the aim is to achieve the required electrical characteristics at the design frequency, rather than to synthesize an effective medium.

Two main approaches have been proposed for the synthesis of metamaterial transmission lines: the dual transmission line model [4] and the resonant-type approach [5-7]. In the former one, a host line is loaded with series connected capacitances and shunt inductances. Resonant type metamaterial transmission lines are implemented by loading a host line either with split rings resonators (combined with shunt inductances) or with complementary split rings resonators (in combination with series capacitances). All these artificial transmission lines exhibit an unusual dispersion diagram, in which two transmission bands, separated by a frequency gap. Within the lower frequency band, the loading elements are dominant and wave propagation is backward (or LH: Left Handed). Namely, the phase and group velocities are anti-parallel and, assuming that the energy flows from left to right (positive direction), the phase constant β, is negative. Left handed wave propagation in this frequency region (lower band) can be interpreted as due to the negative values of the effective permeability and permittivity of the medium, which are achieved thanks to the presence of the loading elements. Alternatively, the unit cell of these artificial lines (host line plus loading elements) can be described through lumped element T- circuit models, from where a simple analysis reveals that the negative series reactance and shunt susceptance (related to the presence of the loading elements) is the origin of backward waves in the first transmission band. In the upper transmission band, wave propagation is forward (or RH: Right Handed) since the line dominates over the loading elements and the signs of the series reactance and shunt susceptance are both positive. In this region, $\beta > 0$ and the phase and group velocities are codirectional. Finally, in the stop band region, the series reactance and shunt susceptance have opposite signs and signal propagation is not allowed. In summary, the artificial transmission lines implemented by means of LC loaded lines or through the resonant type approach exhibit a composite right/left handed behavior. In certain applications, the left handed band is the pass band of interest. In others, the relevant aspect to achieve the required performance is the presence of the two bands (LH and RH). This is the case, for instance, in the design of broadband filters based on a continuous transition between the left handed and right handed bands. In the present article, the controllability of the dispersion diagram of such artificial lines is used for the design of an enhanced bandwidth component with compact dimensions. This was done previously by considering LC loaded lines, but it has never been done by using resonant type metamaterial transmission lines.

A systematic approach is introduced in the present work, and the approach is applied to the design of a rat-race hybrid coupler. In this work, complementary split rings resonators loaded lines are used. By adding series capacitive gaps to these structures, a composite right/left handed behavior arises (as has been indicated above). However, since in the present work only the left handed band of these lines is exploited, we will refer to these lines as left handed lines from now on. It is also possible to implement forward (right handed) artificial lines with controllable characteristics by combining complementary split rings resonators with shunt connected inductances. The topologies of the basic cells for both line types and their corresponding equivalent T-circuit models are depicted in Figure.1(b).

LH AND RH BAND

The layout of strip-shaped CSRRs combined with series capacitance implemented by a series gap and its lumped element equivalent T-circuit model are shown in Figure 1(a). As proposed in [8], under the assumption that the electrical size is small compared with the wavelength and considering the part as the basic cell of periodical structure, the phase shift factor can be obtained:

$$\cos\emptyset = 1 + \frac{C(1-\omega^2 LC_g)(1-\omega^2 L_c C_c)}{2C_g[1-\omega^2 L_c(C_c+C)]} \tag{1}$$

Eq. (1) indicates that the left-hand pass-band occurs in the frequency region:

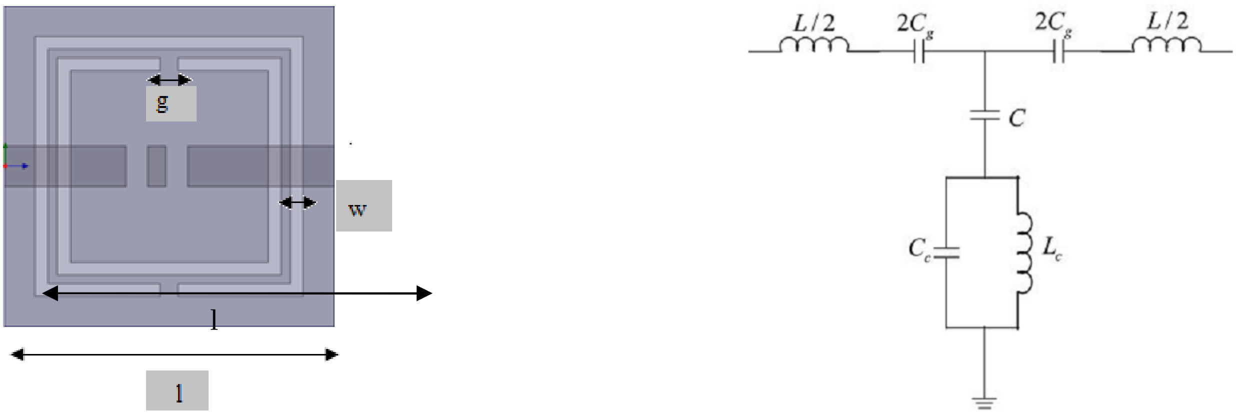
$$f_L = \frac{1}{2\pi}\sqrt{\frac{C+4C_g}{L_c[4C_g(C_c+C)+C(C_c+L)]}} \tag{2}$$

$$f_H = \frac{1}{2\pi\sqrt{L_c C_c}} \tag{3}$$

Right-hand pass-band can be found above the frequency:

$$f_R = \frac{1}{2\pi\sqrt{LC_g}} \tag{4}$$

By adjusting the series capacitance C_g, right-hand pass-band can be moved, and especially as C_g is increased to a certain value a balanced CRLH transmission with wide pass-band can be produced.



(a) (b)

Figure 1: (a) Layout of Strip-Shaped CSRRs Combined with Microstrip Coupled Line (b) Equivalent Circuit Model

COUPLER DESIGN AND RESULTS

A square shaped CSRRs topology and their relevant dimensions are shown in Figure.1 (a). The relevant parameters of the CSRR element wire are l=6.28mm, g=0.5mm, and w=0.4mm. The distance between the periodic elements is 1.72mm. Figure.2 represents the periodic structure that consists of three square shaped SRR structure. The objective in this paper is to design coupler based on the theory of the SRR and CSRR in order to understand the backward-wave phenomenon of the LH material. Backward-wave phenomenon means that the propagation of the wave is in the opposite direction as regards to the conventional case.

Directional coupler is passive device with four ports, as shown in Figure.(2). A coupler has four ports: input, transmitted, coupler, and isolated ports. According to Figure.(2), for the conventional case, port 1 is the incident port, port 2 is the transmitted port, port 3 is the isolated port, and port 4 is the coupled port. For the metamaterial coupler, port 4 is the isolated port, and port 3 is the coupled port, as shown in Figure.(2). Thus, port 3 in the metamaterial coupler is coupled port instead of port 4 in the conventional coupler. The implementation of a simple coupler is based on the coupling of two transmission lines. This is known as a coupled line coupler.

There are two traditional topologies of implementation the coupler, backward (port 3 is coupled port and port 4 is isolated port), and forward (port 3 is isolated port and port 4 is coupled port), as shown in Figure.(2). The coupler can be designed by using the S-matrix with four ports network. For a backward coupler, the requirement for S-matrix is given [9]

$$S_{11} = 0 \quad (5), \quad S_{21} = \frac{\sqrt{1-k^2}}{\sqrt{1-k^2}\cos\emptyset + J\sin\emptyset} \tag{6}$$

$$S_{31} = \frac{jk\sin\emptyset}{\sqrt{1-k^2}\cos\emptyset + J\sin\emptyset} \tag{7}$$

$$S_{41} = 0 \tag{8}$$

where ϕ is the phase shift, k is the coupling factor that is given by $k = (Z_{eo} - Z_{oo})/(Z_{eo} + Z_{OO})$; where Z_{eo} and Z_{oo} are the even characteristic and the odd characteristic impedance ,respectively. According to the assumption of a symmetric structure, even and odd mode analysis lead to the coefficients of the above S-matrix, and the condition to obtain perfect matching at the input port is given by $Z_0 = \sqrt{Z_{eo} + Z_{oo}}$

The assumption shift ϕ (or the phase velocity) for the even and odd modes is roughly the same (which is in turn an assumption valid for quasi-TEM wave propagation). Coupling (i.e. S_{31}) depends on the electrical length of the coupled lines and on the coupling factor k. The optimum coupling is obtained for $\phi = \pi/2$. In this case, the coupling is $|S_{31}|$ = k.

Thus, in these backward wave couplers, maximum coupling depends on the difference between the characteristic impedance for the even and the odd modes. Thus, the coupling is defined by the even and the odd characteristic impedance. It is difficult to implement a good coupling of the backward coupler, because it is limited by the geometrical limitations. On the other hand, it is easy to get this feature of the coupling by using the metamaterial implementation. In metamaterial, the couplers are relatively small, depending on the required coupling, and the bandwidth is reasonably good.

In order to produce the band pass filter we had a capacitor in the microstrip line and then the equivalent circuit for the new CSRR, as shown in Figure.(2). The production of the band pass filter is based on the equivalent circuit for the CSRR [10].

The design of our coupler is based on the article of [11], The simulations of the directional coupler are based on the theory of the square structure (and not based on the circular structure) of the SRR and CSRR. The advantage of this circuit is that the area of the coupling is great as regards to the coupler based on the circular structure. For 36 mm given length, as shown in Figure.(2). From the simulation we can see that the coupler is working in the wireless local area network (WLAN) bandwidth

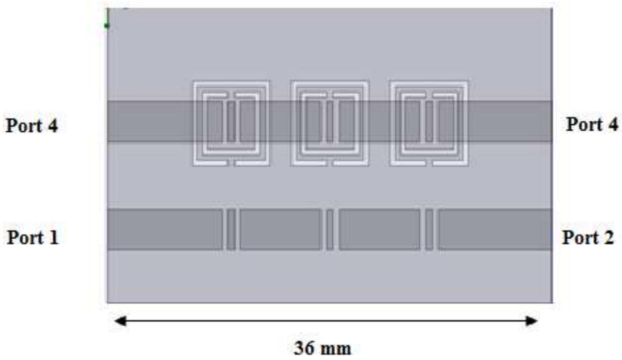


Figure 2: The Simulated Model of the Periodic Structure that Consists of Three Square Shaped CSRR Structure

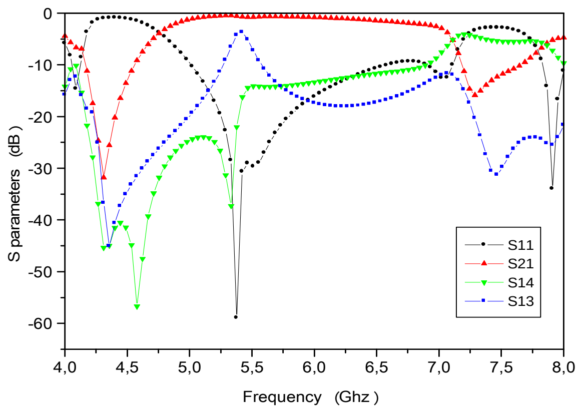


Figure 3: Simulated S-Parameters Coupler for Three-Cell Backward Coupler

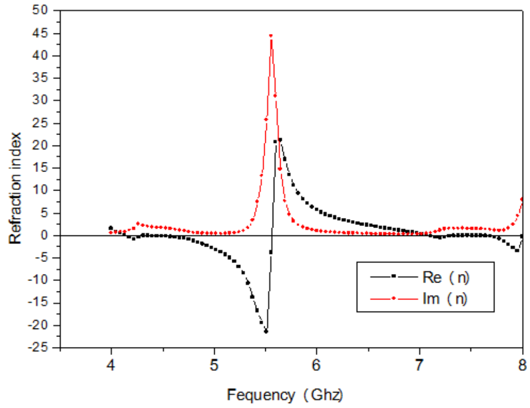


Figure 4: Representation of Index of Refraction for the Coupler

CONCLUSIONS

In this paper, we designed a directional coupler, based on the theory of the split-ring resonators (SRRs), and the complementary CSRRs. A square shaped CSRRs topology and the relevant dimensions are shown in Figure 1(a). The periodic structure that consists of three square shaped CSRR structure is shown in Figure (2). The advantage of this circuit is that the area of the coupling is great as regards to the coupler based on the circular structure. The results of simulation with the miniature structures show the backward-wave phenomenon of the LH material. Backward-wave phenomenon means that the propagation of the wave is in the opposite direction as regards to the conventional case.

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