Different Approaches to the Design of Metamaterials

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Abstract – **Metamaterials and especially left-handed metamaterials present a new paradigm in modern science, which allows design of novel microwave components with advantageous characteristics and small dimensions. In this paper an overview of different approaches to the design of metamaterials is given, together with several practical realizations of the unit cells.**

Keywords – **Metamaterials, split-ring resonators, transmission line approach.**

I. INTRODUCTION

Different techniques and methods, such as defected ground structures (DGS), photonic bandgap structures (PBG), frequency selective surfaces (FSS) etc. are used to improve performances or reduce dimensions of microwave passive devices. Recently, a new approach has emerged, based on the concept of artificial effective media, i.e. application of metamaterials. Metamaterials present a particular class of structured materials which exhibit advantageous and unusual electromagnetic properties, generally not found in nature. They are composed of unit cells in the same sense as matter consists of atoms. The unit cells, whose size is typically smaller then one tenth of the propagating signal wavelength, are made of conventional materials, i.e., finally, of normal atoms. Therefore, metamaterials represent the next level of structural organization of matter.

Due to sub-wavelength dimensions of the unit cells, quasi-static analysis can be performed and the concept of artificial effective media can be applied. Consequently, metamaterials can be considered as a continuous medium with effective parameters, namely effective dielectric permittivity and effective magnetic permeability. By a proper choice of the type and geometrical arrangement of constituent unit cells, the effective parameters of metamaterials can be made arbitrarily small or large, or even negative.

A special sub-class of metamaterials with both effective parameters negative in a certain frequency, are so-called double-negative (DNG) or left-handed (LH) metamaterials. The first theoretical speculation on the existence of DNG media and prediction of their fundamental properties was done by Russian physicist Victor Veselago in 1967, [1]. Veselago anticipated unique electromagnetic properties of DNG media and showed they support propagating modes of the electromagnetic waves, but exhibit negative propagation constant. The energy would still travel forward from the source but the wave fronts would travel toward the source. Consequently, vector of the electric field, vector of magnetic field and wave vector of an electromagnetic wave in a double-negative material will form a left-handed triad. Therefore, LH materials are characterized by antiparallel phase and group velocities and exhibit negative refractive index (NRI).

However, the first experimental verification of the existence of LH metamaterials occurred more then three decades later. The first particle that exhibits negative permeability at microwave frequencies, consisting of thin metallic wires, was proposed by Pendry in 1996, [2]. Three years later, the same author presented a new sub-wavelength particle called split-rings resonator (SRR) that provides negative permeability, [3]. By combining two Pendry's particles into one unit cell, Smith and Shultz performed the first experimental verification of negative index of refraction and LH behavior, [4], and Science magazine named LH metamaterials as one of the top ten scientific breakthroughs in 2003, [5]. Following this experimental verification, many researchers have further studied the characteristics and applications of such LH metamaterials, [6], [7]. Since LH behavior is obtained due to the resonant nature of the unit cell, all structures based on the application of SRR are called resonant LH metamaterials.

In mid 2002, three groups of researchers simultaneous proposed new non-resonant approach to the design of planar LH metamaterials based on the dual transmission line (TL) concept, [8], [9], [10]. While the first (resonant) approach results in narrow-banded LH structures, the second one (TL) provides a useful tool for the design of simultaneously low loss and broad bandwidth devices.

The main goals of current research in the field of metamaterials are further miniaturization and performance improvement of the unit cell. To that aim, a third hybrid approach is also used, which combines sub-wavelength particles from both the resonant and non-resonant approaches into one unit cell. In this paper, all three approaches to the design of LH metamaterials are explained in detail, and several practical realizations of the unit cells are presented.

II. RESONANT APPROACH

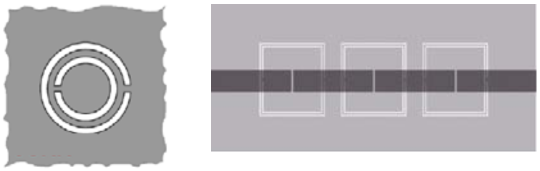
To produce LH behavior, two different particles need to be combined into a unit cell, one that provides negative permittivity and the other that provides negative permeability. The resonant approach is based on the application of SRR particles, Fig 1a, that, when exposed to axial magnetic field, exhibit extreme values of effective magnetic permeability in the vicinity of resonance, namely highly positive/negative in a narrow band below/above the quasi-static resonant frequency of the rings. An array of SRRs has filtering properties, and, when properly polarized, can inhibit signal propagation, thus offering an effective way to reject a frequency band in the vicinity of its quasi-static resonance, [11].

(a) (b)

Fig. 1. (a) Split-ring resonator, SRR,
(b) SRR-loaded microstrip line

In the microstrip technology, SRRs can only be etched in the upper substrate side, next to the host transmission line, Fig 1b. A microstrip line loaded with SRRs is a single-negative medium, and therefore exhibits a stop-band characteristic. To improve the coupling, the distance between the line and the rings should be as small as possible. This geometrical layout is not always adequate, because in many applications the miniaturization is primary request. Although having a narrow frequency range with negative permeability, the configurations using SSR have driven a lot of attention, [6], [7].

Apart from the microstrip technology, SRR can be successfully used in waveguides as well, especially to allow propagation below the cut-off frequency. A number of results have recently been reported in the literature, [12], [13].



(a) (b)

Fig 2. (a) Complementary split-ring resonator, CSRR,
(b) Resonant LH line with N=3 unit cells composed of square CSRR and a gap; both top (dark grey) and bottom (light grey) conductive layers are shown.

Using the Babinet principle, a complementary split ring resonator (CSRR) was proposed in [14], Fig. 2a. In the microstrip technology, CSRRs are etched in the ground plane underneath the microstrip. Since CSRRs are excited by the electric field, they produce negative effective permittivity. In order to obtain LH behavior, a particle that introduces effective negative permeability has to be added. This is achieved by periodically etching capacitive gaps in the host microstrip line. A typical LH resonant line with N=3 unit cells is depicted in Fig. 2b. This structure behaves as a band pass filter with a sharp transition in the lower band edge, Fig 3. However, it exhibits poor frequency selectivity in the upper transition band.

Equivalent circuit of one unit cell of the resonant LH line is shown in Fig. 4, where the parallel resonant circuit with inductance L_r and capacitance C_r models the CSRR and the host microstrip line is represented by the inductance L. The gap is modeled by the inductance C_g. The CSRR is electrically coupled to the host microstrip line through the line capacitance C_c.

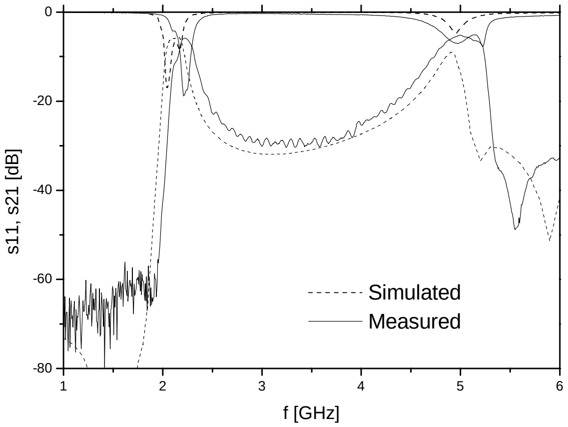


Fig. 3. Simulated and measured transmission and reflection coefficients of resonant LH line with N=3 unit cells.

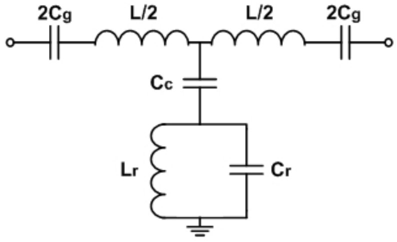


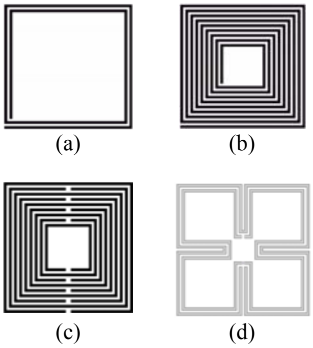
Fig. 4. Equivalent circuit of one unit cell of the resonant LH line.

With the aim of miniaturization, other resonant sub-wavelength particles have recently been proposed, such as the broadside coupled SRR, [15], spiral resonator (SR), [16], as well as multiple geometries, namely the multiple SRR and the multiple SR, [17]. Fractal curves have also been employed in order to obtain the maximal circumference of the rings on the smallest substrate area, [18].

Spiral resonators with different number of turns are shown in Fig 5a and 5b. SR exhibits a great potential for the miniaturization of the unit cell, [16], since it reduces the dimension of a particle for more then 40%, for the fixed resonant frequency. However, the application of SR is directly connected with significantly increased insertion losses.

If two concentric rings with splits on the opposite sides are used instead of just one, capacitance and inductance of the structure are greatly increases, [3], and resonant frequency is lowered. Therefore, multiple SRRs/CSRRs that consist of N concentric rings, Fig.5c, can be used in order to reduce dimensions of the unit cell, [17]. Also, when N is increased, the second harmonic is significantly shifted towards the higher frequencies, thus creating a wide and deep stop band in the transmission characteristics, Fig. 6. However, certain saturation can be observed for higher values of N. Adding more then 5 concentric rings results in a very small change of the performances: resonant frequency is lowered for less then 1%, while the other parameters also vary very slightly.

The same behavior can be observed in the case of the SR with number of turns greater then 7. The explanation of this phenomenon is that the efficiency of excitation of the particle by axial magnetic field deteriorates when its middle section is occupied. For that reason, only multiple geometries with $N<5$ should be used.


(a) (b)

(c) (d)

Fig. 5. Resonant sub-wavelength particles: (a) spiral resonator, SR, (b) multiple SR, (c) multiple SRR, and (d) square Sierpinski SRR.

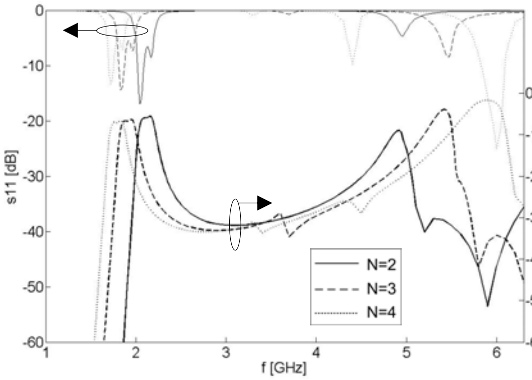


Fig. 6. Simulation results for LH lines that use multiple CSRRs with N concentric rings.

Fractal curves are well known for their unique space-filling property. In Fig. 5d, SRR designed by using square Sierpinski fractal curve is shown. The measurement results show that the application of fractal geometry reduces resonant frequency for more than 35% for fixed dimensions of the unit cell, and simultaneously improves frequency selectivity at both sides of the pass band. Furthermore, a wide and deep stop band is observed, due to the suppression of the second harmonic for more than 22dB, [18].

It is widely accepted that the orientation of the particle influences the performances only in the case of SRR-loaded microstrip lines, not in the complementary case or waveguide technology. However, the orientation has to be taken into account in the design of all other metamaterial structures, [19]. The influence of the orientation to the performances is especially visible in the case of multiple CSRRs.

The main disadvantages of resonant LH metamaterials are the following. Firstly, the resonant approach is based on the application of SRR or similar particles, which provide LH behavior only in a narrow frequency range. Secondly, resonant metamaterials are not isotropic, since LH behavior exists only for specific polarization of the electromagnetic field. Nevertheless, resonant LH metamaterials are successfully applied in the design of filters and frequency selective surfaces.

III. TRANSMISSION LINE APPROACH

TL theory provides a powerful tool for analysis and design of conventional (right-handed, RH) materials. The basic idea behind the TL approach to the design of metamaterials is that standard TL theory can be used to analyze and design LH metamaterials using a dual concept, [8], [9], [10].

A dual transmission line can be described by an equivalent circuit that is the dual of the circuit that models a conventional transmission line. In the dual case, the capacitors are connected in series, while the inductors are placed in a shunt configuration. If the unit cells are sufficiently small (much smaller then the propagating signal wavelength), such structure can be regarded homogenous, i.e. effective permittivity and permeability can be calculated. It has been shown that dual transmission line exhibits negative effective permittivity and permeability in a certain frequency range and, therefore, behaves as LH transmission line. LH TL is obviously of high-pass nature, in contrast to the RH TL, which is of low-pass nature.

Because of unavoidable RH parasitic series inductance and shunt capacitance, purely LH structure does not exist. Instead, a composite right/left-handed (CRLH) structure represents the most general model of a structure with LH attributes. Equivalent circuit of a unit cell of CRLH TL is shown in Fig. 7. By comparing circuits shown in Fig. 4 and Fig. 7, it can be seen that the only difference between the resonant and the TL approach lays in the existence of the coupling capacitance C_c in the former case. Indeed, it can be shown that the resonant case presents a sub-class of the TL case.

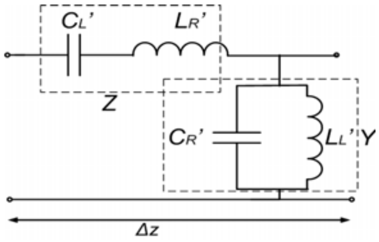


Fig 7. Unit cell of a CRLH TL.

Homogeneous CRLH TL does not exist in nature, but it can be constructed by cascading a number of CRLH unit cells. Unit cell can be realized by using lumped components, but in that case only a limited set of element values is available. If microstrip technology and semi-lumped approach are used, elements of the unit cell can have arbitrary values. The first CRLH unit cell of this type was proposed in [9], that uses interdigital capacitor for obtaining LH capacitance C_L and grounded shunt stub inductor for LH inductance L_L, Fig 8. RH capacitance C_R

always exists due to the capacitance of the host microstrip line to the ground plane, and RH inductance L_R is caused by the magnetic flux generated by the current flow in the digits of the interdigital capacitor. The measured transmission and reflection coefficients of LH TL constructed by cascading 12 unit cells of this type are reprinted from [7] in Fig. 9. It can be seen that LH TL exhibits almost 100% wide LH frequency band, which represents its major advantage over the similar resonant type LH structures. However, this wide LH range is not ripple-free. Another advantage of the TL approach is that it can easily be generalized into two or even three dimensions, by simple cascading of the unit cells in different directions, [14].

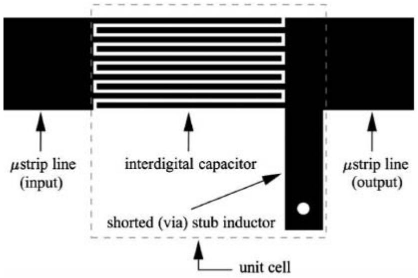


Fig. 8. CHRL TL unit cell in microstrip technology.

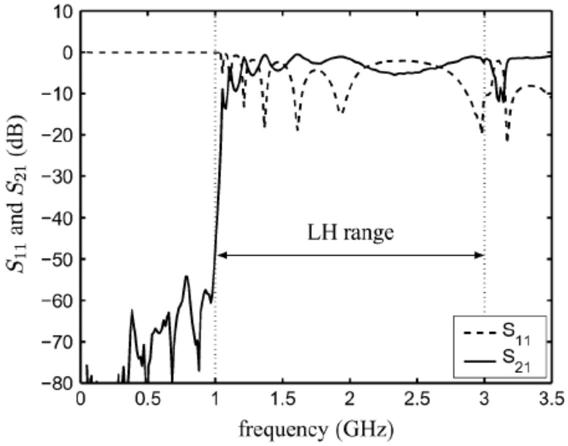


Fig 9. Measured transmission and reflection coefficients of LH TL that consists of 12 unit cells, reprinted from [9].

By using the LH TL approach, a number of novel microwave devices have been proposed, such as leaky-wave antennas, different couplers, zeroth order resonator, planar lens, etc., [20]. However, in all cases application of the unit cell shown in Fig. 8 resulted in very high insertion losses. This has led to the conclusion that small dimensions achieved by the application of LH structures are always tied in with relatively high insertion losses.

Recently, this drawback has been overcome by novel LH unit cell called ForeS, [21], [22]. Although very compact ($\lambda g/13$ by $\lambda g/13$), ForeS exhibits low insertion losses and large design flexibility: small changes of its inner dimensions, result in resonant frequency tuning range approximately equal to 67%. In the same time, the second harmonic is positioned at more then four times the first resonant frequency. By placing the diodes at the relevant positions, denoted in Fig. 10, ForeS can be made electronically reconfigurable: 27% resonant frequency tuning range can be achieved, as well as different in- and out-of-band performances.

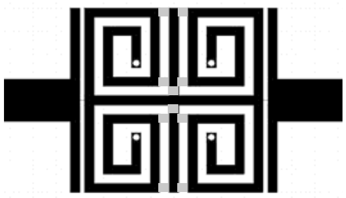


Fig 10. ForeS unit cell; light patches indicate the positions at which diodes can be placed, for electronic configurability.

More compact ($\lambda g/16$ by $\lambda g/32$, $\lambda g/16$ by $\lambda g/15$ and $\lambda g/19$ by $\lambda g/16$) unit cells with similar performances as ForeS have been introduced in [23] for the design of miniature low-loss and highly selective filters in 1-2GHz frequency band. The cells consist of two and four rectangular grounded spirals, which are both mutually coupled and end-coupled to the microstrip line.

Super-compact ($\lambda g/59$ by $\lambda g/27$) LH unit cell called S-spiral has been proposed in [24]. The proposed structure shows lower insertion loss at resonant frequency and higher Q-factor in comparison with all previously reported LH resonators. Using S-spiral, band pass filters of the second and the third order have been designed, characterized by extremely compact size, very narrow 1dB bandwidth and small insertion loss. Layout of one of the filters is shown in Fig. 11 and its response is depicted in Fig. 12.

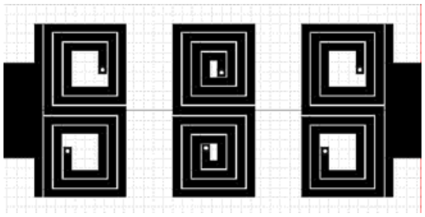


Fig. 11 Layout of the optimized band pass filter of the third order that uses S-spiral unit cells.

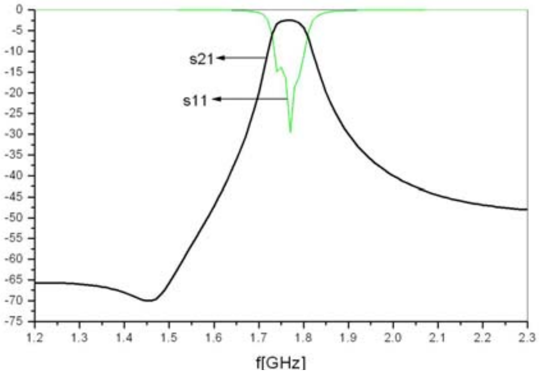


Fig. 12 Simulated transmission and reflection coefficients of the third-order filter that order that uses S-spiral unit cells.

IV. HYBRID APPROACH

Hybrid approach combines particles from two other approaches: SRR and CSRR from one side and gaps and shunted stubs from the other side. Generally, SRRs and gaps provide negative permeability, while CSRRs and stubs provide negative permittivity. Using various combinations of these particles, hybrid LH metamaterials can be designed.

Unit cell that combines shunted stubs and CSRRs was presented in [25]. It has been used for the design of compact ultra-wide band pass filters. However, it should be noted that the pass band obtained in this way is not entirely LH in nature.

Other combinations of particles can also be used. Unit cell that consists of SRR-loaded microstrip line and an inductive stub is depicted in Fig 13. Optimization of the dimensions of both the SRR and the stub plays a crucial role, since they should both operate at the same frequency to produce LH behavior. Simulation results of the optimized case are shown in Fig 14. LH pass band is obtained in a narrow range around 4.13GHz. Rather turbulent transition between RH and LH pass bands is due to different widths of frequency ranges in which shunt stub and SRR produce negative permittivity and permeability, respectively.

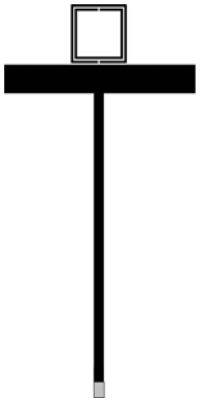


Fig 13. Unit cell that consists of SRR-loaded microstrip line and an inductive stub.

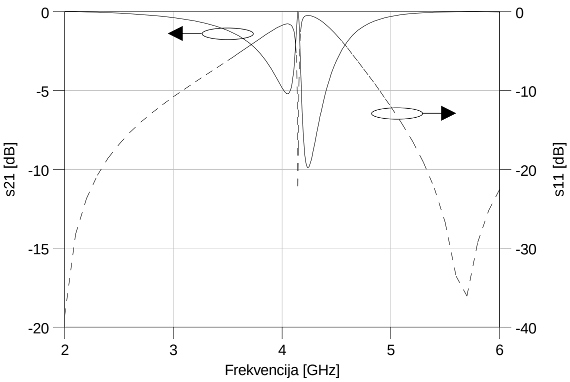


Fig. 14. Simulated transmission and reflection coefficients of the unit cell composed of SRR and shunt stub.

Another unit cell can be made as combination of SRR and CSRR, Fig. 15. Again, optimization procedure has to be employed, since SRR and CSRR with the same dimensions do not resonate at exactly the same frequency. The results of optimization procedure are illustrated in Fig. 16, where dimensions of the CSRR are changed, while SRR remained the same. Since both particles result in a single-negative medium, two stop bands with rather high insertion can be observed. However, in the optimized case when CSRR is 4.4mm wide, relatively low insertion can be seen, that corresponds to the LH pass band.

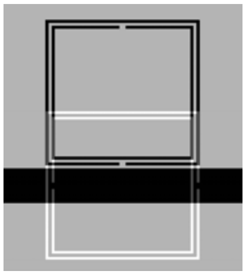


Fig. 15. Unit cell that consists of SRR and CSRR; both top (black) and bottom (grey) conductive layers are shown.

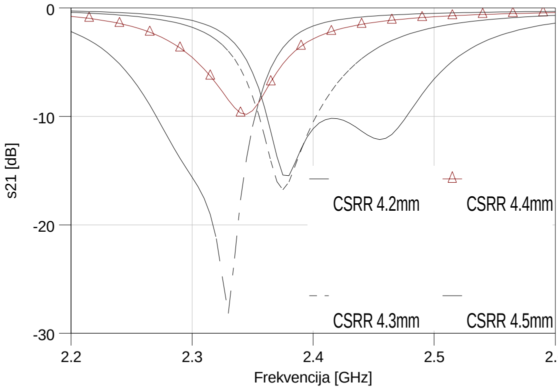


Fig .16. Simulated transmission coefficient of the unit cell that consists of SRR and CSRR. Outer dimensions of SRR are 4.8x4.8mm, while the dimensions of CSRR are varied.

It is also possible to design LH lines with more then two particles. The third particle can be used to control the response, for example to introduce an additional transmission zero. Such unit cell, which combines shunt stub, gap and CSRR, was presented in [26]. Combination of CSRR and gap produces steep left side of the pass band, while stub and CSRR result in steep right side. In this way, LH line with a symmetrical response is obtained.

V. CONCLUSION

Depending on the application, the designer is faced with the choice between resonant, non-resonant or hybrid approach to metamaterials. Although characterized with narrow LH frequency range and high anisotropy, resonant metamaterials can be successfully applied in the design of filters and frequency selective surfaces. On the other hand, typical TL-based metamaterials exhibit very wide LH ranges, but suffer from high ripple in the pass band. Hybrid structures, that combine particles from both approaches, can be used to improve characteristics of microwave devices, such as to increase frequency selectivity of the filter etc.

It has been generally accepted that the application of LH metamaterials is always tied in with relatively high insertion losses, although it also results in very compact structures. Recently, this drawback has been overcome by novel LH unit cells based on grounded spirals that exhibit super-compact dimensions together with low insertion losses and high Q.

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