TUTORIAL PAPER

METAMATERIALS: CHARACTERISTICS, DESIGN AND MICROWAVE APPLICATIONS

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Abstract: We present an overview of unique properties of metamaterials, especially negative index materials. These have allowed novel applications, concepts and devices to be developed in the past decade. A review of the progress made in this field is presented with a focus on microwave devices and applications in wireless communications. Since a metamaterial can be regarded as a continuous medium with effective dielectric permittivity and effective magnetic permeability, we present the procedure for the extraction of effective electromagnetic parameters for a guided wave structure with split-ring resonators. As examples, our own designs of bandpass and triple-band filters, which are constructed using metamaterial-inspired resonator elements, are presented and discussed.

Keywords: metamaterials, left-handed materials, negative-index of refraction materials, split-ring resonator

1. INTRODUCTION

Metamaterials are artificial, usually periodic structures which exhibit advantageous and unusual electromagnetic properties. According to [1], a metamaterial is defined as: "*an object that gains its electromagnetic material properties from its structure rather than inheriting them directly from the material it is composed of* ". The term metamaterial was also defined as "*macroscopic composites having a synthetic, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation* " [2,3].

The size of the unit cells of metamaterials is typically smaller than one tenth of the propagating signal wavelength. Due to the small size, it can be considered to form an effective medium with an effective dielectric permittivity and effective magnetic permeability which represents the bulk artificially constructed medium. By a proper design of constituent unit cells, the effective parameters of metamaterials can be made arbitrarily small or large, or negative.

Metamaterials are generally implemented in a periodic configuration although this is not a requirement. From a fabrication point of view it is easier to design and build by repeating a cell than by using different cells. Also, making metamaterials periodic allows one to use well-established theory of periodic structures, where a non-uniform structure would be much more difficult to analyze.

Possible properties of materials in the ε-μ domain are shown in Fig. 1. The first quadrant ($\varepsilon > 0$ and $\mu > 0$) of the ε-μ diagram in Fig. 1, represents right-handed

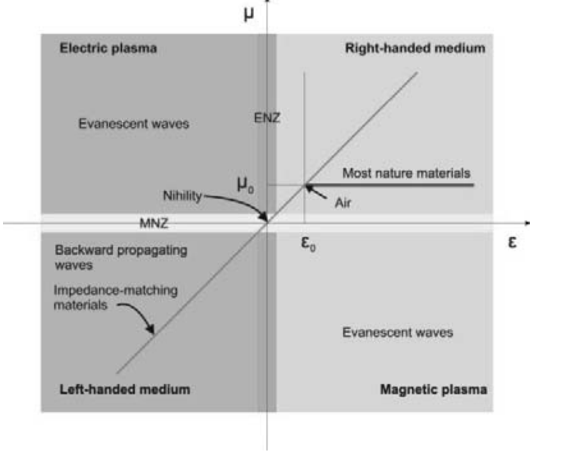


Figure 1. Possible properties of isotropic and lossless materials in the ε-μ domain. ENZ denotes an ε-near-zero material, while MNZ is a μ-near-zero material. Based on [2].

materials (RHM), which support forward propagating waves.

The blue line in Fig. 1 represents the materials found most commonly in nature with a permeability μ_0 and permittivity larger than ε_0. Although this is not always emphasized, even for a RHM the material properties typically vary with frequency. In this quadrant, the electric field **E**, the magnetic field **H**, and the wave vector **k** form a right-handed system, as described by Maxwell's equations.

The second quadrant ($\varepsilon < 0$ and $\mu > 0$) describes electric plasmas which support evanescent waves. The fourth quadrant ($\varepsilon > 0$ and $\mu < 0$) also supports evanescent waves. These are both single negative (SNG) quadrants, meaning that only one effective parameter is negative.

The third quadrant (ε < 0 and μ < 0 or double negative (DNG)) contains the left-handed materials, which were proposed in 1967 [4]. In LHM, the electric field **E**, the magnetic field **H**, and the wave vector **k** form a left-handed system and these support "backward" propagating waves. The term backward refers to the opposite sign of group and phase velocity. The index of refraction $n = \sqrt{\varepsilon_r \mu_r}$ is negative.

Nature favours conventional RHM (quadrant 1) which can exist at any frequency, and to lesser extent single negative (SNG) materials (quadrants 2 and 4), available only in restricted frequency bands. Yet the laws of physics do not prohibit the existence of LH materials. This provides the third quadrant of the ε-μ diagram in Fig. 1. In order to satisfied the generalized entropy conditions, LH materials need to be frequency dispersive, i.e. their propagation constant β has to be a nonlinear function of frequency.

Most of the initial interest in the metamaterial field was directed at investigating materials in the third quadrant. Although metamaterials were first known as left-handed materials (LHMs) or negative index materials (NIMs), the metamaterial concepts includes much more than the LHM which occur in the third quadrant. Disadvantages are that devices based on LHM are usually narrow band and display high losses.

Not all work in the metamaterial field is concentrated on LHM or DNG materials. For example, the point $\mu = -\mu_0$ and $\varepsilon = -\varepsilon_0$ represents anti-air in the LHM region, which will produce a perfect lens; the point μ = 0 and ε = 0, the zero refractive index point or nihility, which finds application in the design of highly directive antennas and also multiband antennas [5]; the line μ = ε in both RHM and LHM regions represents impedance matching materials, which have perfect impedance matching with air, resulting in no reflections. Also, the vicinity of μ = 0 is called as μ-near-zero (MNZ) material, and the vicinity of ε = 0 is a ε-near-zero (ENZ) material [2]. Both these have special applications such as supercoupling, squeezing energy and field confinement in narrow channels [6], [7]. Various applications were demonstrated for small antennas using electrically small dipoles with SNG or DNG shells to improve the antenna efficiency [5].

The development of metamaterials started with a Russian scientist, Veselago [4], who speculated about the theory of LHM and the possible properties in his paper titled "*The electrodynamics of substances with simultaneously negative values of* ε *and* μ". The paper was first published in Russian in 1967 and a year later in English.

Figure 2. The array of split-ring resonators plus wire assemblies used for the experiment. Adopted from [11].

The next milestone was the introduction by Pendry of a thin wire structure as a negative-ε medium by decreasing plasma frequency into microwave range [8] and a negative-μ split-ring resonator structure [9] operating in microwave range. Smith et al [10,11] then combined the thin wire structure with split-ring resonators to demonstrate experimentally that a LH structure can be implemented in the microwave frequency range. This is shown in Fig. 2. The split-resonant type metamaterial elements are discussed in section 3.1.

Eleftheriades [12], Caloz and Itoh [13], and Oliner [14] did similar work around the same time and introduced non-resonant, low-loss and broad-bandwidth, transmission line (TL) metamaterials. Their approach is discussed in more detail in section 3.2.

Smith et al [15] introduced the gradient refraction index medium to continuously bend electromagnetic waves, which is different from metamaterials where the elements are all identical (e.g. Fig. 2). In the gradient material the properties vary with position, to obtain a refractive index that also varies with position. Pendry proposed an optical transformation in 2006 which find application in invisibility cloaks to control the propagation of electromagnetic waves [16].

Twelve books and one new journal on metamaterials have been published since 2003:

- S. Zouhdi, A. Sihvola and M. Arsalane, *Advances in Electromagnetics on Complex Media and Metamaterials,* Springer 2003.
- S. Tretyakov, *Analytical Modelling in Applied Electromagnetics*, Artech House, 2003.
- G. V. Eleftheriades and K. G. Balmain, *Negative-Refraction Metamaterials: Fundamental Principles and Applications,* Wiley-IEEE Press, 2005.
- C. Caloz and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*, Wiley-IEEE Press, 2006.
- N. Engheta and R. W. Ziokowski, *Metamaterials: Physics and Engineering Explorations*, Wiley-IEEE Press, 2006.
- Sir J. B. Pendry, *Fundamentals and Applications of Negative Refraction in Metamaterials*, Princeton University Press, 2007.
- R. Marques, F. Martin and M. Sorolla, *Metamaterials with Negative Parameters*, Wiley, 2007.

- C. M. Krowne and Y. Zhang, *Physics of Negative Refraction and Negative Index Materials, Optical and Electronic Aspects and Diversified Approaches*, Springer, 2007.
- S. A. Ramakrishna and T. Grzegorczyk, *Physics and Applications of Negative Refractive Index Materials*, SPIE and CRC Press, 2009.
- B. A. Munk, *Metamaterials: Critique and Alternatives*, Wiley, 2009.
- T. J. Cui, D. R. Smith, R. Liu, *Metamaterials Theory, Design and Applications,* Springer 2010.
- W. Cai, V. Shalaev, *Optical Metamaterials, Fundamentals and Applications*, Springer, 2010.
- A new Elsevier journal titled "Metamaterials" [17] was founded in 2007.

2. GENERAL PROPERTIES

Several physical phenomena are reversed in LH media and at the intersection between LH and RH media. This is due to the opposite sign of phase and group velocities. These are the Doppler effect, Vavilov-Čerenkov radiation, Snell's law, Goos-Hänchen effect, lensing effect (convex lenses produce diverging rays, which is opposite to RH lenses), and sub-wavelength focusing of an image by a flat slab. Some of these effects are illustrated in Fig. 3.

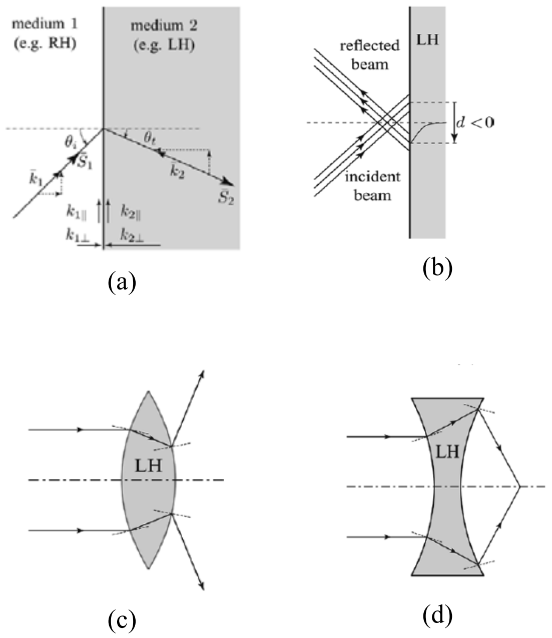


Figure 3. Reversed phenomena in LH metamaterials: (a) Snell's law, (b) Goos-Hänchen effect, (c) concave LH lens diverges, (d) convex LH lens converges. Adopted from [18].

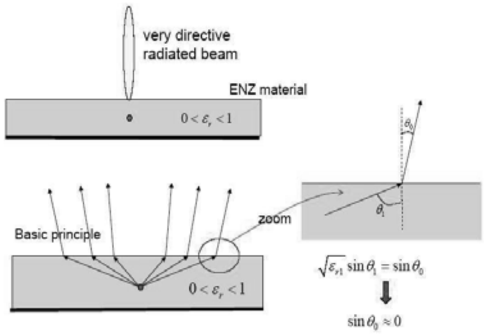


Figure 4. Application of an epsilon near-zero (ENZ) metamaterials in design of a small antenna with high directivity.

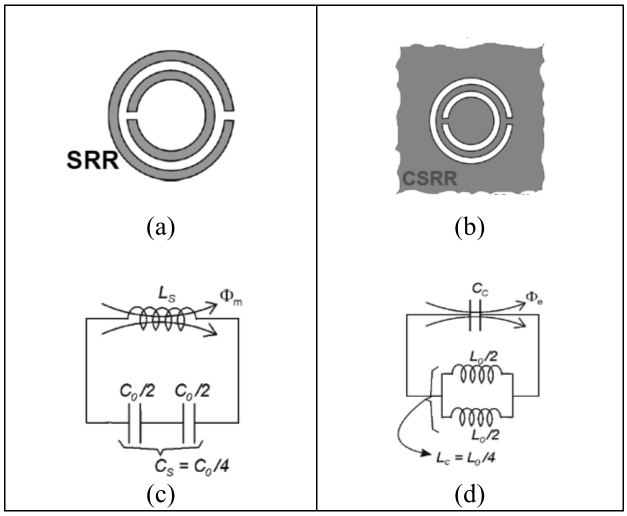


Figure 5. Split-ring resonator (SRR) (μ < 0) and complementary split-ring resonator (CSRR) (ε < 0) and equivalent circuits. Adopted from [40].

Besides LH materials, metamaterials with a permittivity very close to zero (ENZ) can find very useful applications in design of small antennas with a very high directivity, as shown in Fig. 4. To achieve high directivity a classical antenna design requires an electrically large antenna, but if the antenna source is placed in ENZ MMs, all radiation can be focused in the direction which is almost normal to the interference between
air and the ENZ MM, since index of refraction of ENZ media is close to zero. It follows from Snell's law that in Fig. 4, $\theta_0 \approx 0$:

$$n_1 \sin\theta_1 = n_0 \sin\theta_0 \quad (1)$$

3. MICROWAVE APPLICATIONS

Applications of LH metamaterials (MMs) in microwaves are numerous and opened the door to new strategies in design of microwave devices, also referred to as dispersion engineering, which considers and controls the phase response of devices.

There are two main approaches in design of microwave circuits using metamaterials: the *resonant approach* which uses thin wires, split-ring resonators (SRRs) and complementary split-ring resonators (CSRRs) [19], [20] and the *transmission line approach* [21] based on dual transmission line theory. The first one leads to lossy and narrow-band circuits, while the second, non-resonant approach, provides design tools for broad bandwidth devices with low loss.

3.1 Resonant Approach

Split-ring resonators exhibit extreme values of magnetic permeability in the vicinity of quasi-static resonant frequency, when they are excited by means of an axial magnetic field. They behave as an LC resonant tank as it is shown in Fig. 5(a). Although having a narrow frequency range with negative permeability, SRR based configurations attracts a lot of attention. In microstrip technology, SRRs can only be etched in the upper substrate side, next to the microstrip line. Array of SRRs exhibits filtering properties, and when properly polarized, can reject signal propagation.

The complementary split-ring resonator (CSRR) is the dual of the SRR, by the Babinet principle. The CSRR has metallization removed from the ground plane to form the inverse shape to that of the SRR. CSRRs are normally placed adjacent or directly underneath microstrip lines. Interesting filter applications have been demonstrated using CSRRs [20,22]. Periodic gaps in the microstrip line, together with the CSRR, produce a LH response in a narrow frequency band.

Other small elements useful for miniaturization have also been proposed, for example the broadside coupled split-ring resonator (BC SRR) [23], the spiral resonator (SR), [24,25], multiple CSRRs [26] and square Sirpinski fractal CSRRs [27].

Fig. 6 shows a LH microstrip line loaded with CSRRs which provide a negative permittivity, while capacitive gaps in microstrip line give a negative permeability. This line acts as a passband filter since both ε and μ are both negative in the passband.

3.2 Transmission Line (TL) Approach

Transmission line theory has always been a useful tool for analysis and design of microwave circuits. The homogeneous models of pure RH and LH lossless transmission lines are shown in Fig. 7 (a).

It can be seen that the LH TL introduced in Fig. 7(a) on the right, is the dual of the RH TL, i.e. the RH TL is a low pass filter, while the LH TL is a high pass filter. The average unit cell size is represented by Δz and can be much smaller than λ_g, at should be at least less than $\lambda_g/4$. In reality, a pure LH TL cannot exist due to the inevitable RH parasitic series inductance and parasitic capacitance. Therefore, a Composite right and left-handed CRLH TL in Fig. 6 (b) (RH parasitic contribution is denoted in red) is the most general representation of the structure with LH attributes in some frequency bands.

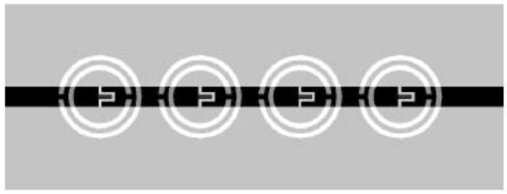


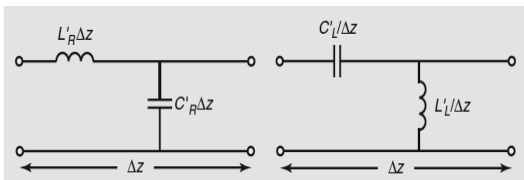
Figure 6. Microstrip line (black) with CSRRs etched in ground plane (gray). Capacitive gaps have been etched on the strip to obtain a left-handed passband. Adopted from [20].

Therefore, a Composite right and left-handed CRLH TL in Fig. 7(b) (RH parasitic contribution is denoted in red) is the most general representation of the structure with LH attributes in some frequency bands.

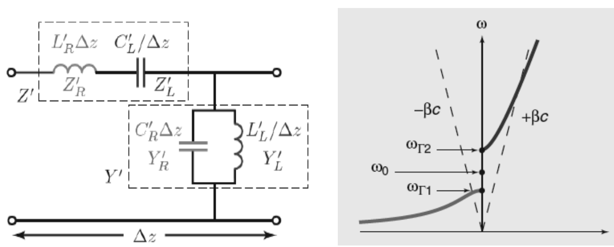
The CRLH TL exhibits a stop band in the β-diagram between $\omega_{\Gamma 1}$ and $\omega_{\Gamma 2}$ (Fig. 7(b)), which do not exist in pure RH and LH TLs. In the case where shunt and series resonances are equal:

$$L_R^{'} C_L^{'} = L_L^{'} C_R^{'} \tag{2}$$

The RH and LH contributions exactly balance each other at the given frequency ω_0 and the stop band is removed. This condition is referred to as the *balanced case*.



(a)



(b)

Figure 7. Equivalent circuit models of: (a) homogeneous RH and LH transmission line, (b) Composite right/left handed (CRLH) TL with β-diagram. The LH band is red and the RH band is blue. Adopted from [21]

The phase constant splits distinctly into two parts β_L and β_R at the frequency ω_0. At that frequency β becomes equal to zero, which means that guided wavelength becomes infinite

$$\lambda_g = \frac{2\pi}{|\beta|} \quad (3)$$

An example of composite right/left handed microstrip line, which is loaded with non-resonant elements like interdigital capacitors and shunt inductors connected to ground is shown in Fig. 8.

Although, at first glance, the resonant and transmission line approaches look very different, they belong to the same *generalized transmission line theory of metamaterials* [28]. To obtain a desired phase response, transmission line can be loaded either with lumped inductance and capacitance (TL approach), or with SRRs and CSRRs which behave as a quasi-lumped elements (resonant approach). It was shown that balanced case and broadband behaviour is not unique characteristics of metamaterials designed by TL approach. They are also realizable with resonant type unit cells as CSRRs, which are coupled to a host transmission line [29].

3.3 Basic advantages of MMs

The main relevant aspect of MMs is the possibility of implementing miniaturized components due to the small electrical size of its constitutive elements, together with improved performance related to its unique and controllable dispersion characteristics. This offers new challenges for the design of inexpensive 1-D and 2-D beam-scanning antennas without phase-shifters and small multi-band antennas with superior performance and low cost, that is not easy achievable through established approaches.

The essential advantages of the MM-based technology are the following:

- Extremely small unit cells resulting in super-compact resonators,
- Zeroth-order resonance existing in LH metamaterials, resulting in small antennas whose resonance is independent of the physical length,
- Zero phase-shift on any length of LH transmission line, when operated at the transition frequency between RH and LH region, resulting in less complex antenna feeding networks,
- Multi-band concept of CRLH TL, resulting in arbitrary (non-harmonic related) choice of operating frequencies of multi-band devices,
- Electrical controllability of unit cells resulting in reconfigurable microwave devices,
- Fabrication using conventional technologies and low cost materials resulting in cost effective microwave devices and antennas.

Multiband operation at arbitrary, nonharmonic related frequencies becomes possible due to nonlinear phase characteristics of a CRLH TL [30], as illustrated in Fig. 9. It can be seen that the dual-band filter has first and second passbands located at the frequencies f_0 and $3f_0$ for the conventional right-handed (RH) line consisting of quarter-wavelength resonators. If we replace the RH line with the CRLH TL, the amplitude response of the filter (Fig. 9(a)) can be mapped to the amplitude response shown in Fig. 9(c) via nonlinear phase response of CRLH TL (Fig. 9(b)). The corresponding position of the centres of passbands f_1 and f_2 can be arbitrarily spaced depending only on the engineered phase response.

Some applications of MMs include dual-band and enhanced-bandwidth microwave devices such as couplers, phase shifters, power dividers [31], mixers, super-compact (i.e. super slow-wave) structures, zeroth-order resonators with constant field distribution [32], tightly coupled-line phase/impedance couplers [33], and series-fed linear array with reduced beam squint [33], which increases scanning range from 2.67 GHz for conventional delay line to 10.44 GHz for metamaterial line, giving an improvement of 290%.

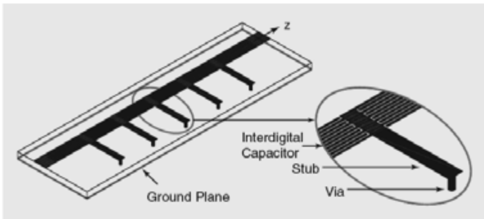


Figure 8. Microstrip composite right/left handed line consisting of interdigital capacitors and shorted stub inductors. Adopted from [21].

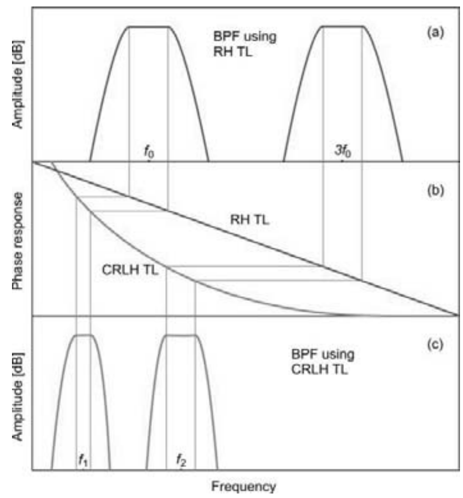


Figure 9. (a) The amplitude response of the conventional bandpass filter, (b) The phase response of RH transmission line and composite right-left handed line, (c) The amplitude characteristic of dual-band filter with nonharmonic related band spacing. Adopted from [30].

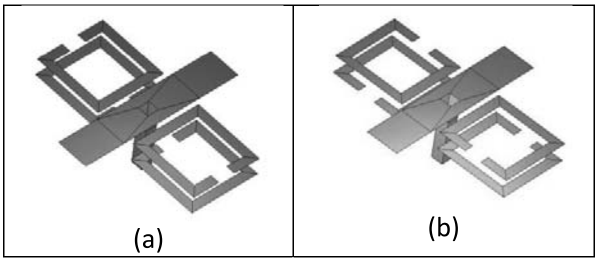


Figure 10. (a) Basic configuration of metamaterial's unit cell, (b) SRRs are rotated by 90 degrees.

4. EXTRACTION OF EFFECTIVE PARAMETERS

To characterize metamaterials, the effective medium theory is used since the wavelength of excitation is much longer than the dimensions of the constituent elements. Here we present the effective parameter extraction for a 1-D LH microstrip line consisting of the periodically loaded thin wires and split-ring resonators (SRRs) along the two-layer microstrip line [35].

The electromagnetic parameter extraction is based on the idea of replacing the unit cells of a metaline by an equivalent microstrip line with homogeneously filled effective permittivity ε_{eff} and permeability μ_{eff}. The fields in the equivalent structure should be equal to the mean fields in the original structure. The equivalent microstrip line has the same line width as an original one and also the same substrate thickness. Effective parameters can be extracted from either simulated or measured scattering parameters. This method is applicable to the unit cells which are symmetrical in respect to the inputs, i.e. only if s_{11} is equal to s_{22} [36].

The propagation constant γ can be determined by a Bloch wave analysis:

$$\gamma = \pm \frac{1}{L} \cosh^{-1} \frac{1 - s_{11}^2 + s_{21}^2}{2 s_{21}} = \pm \frac{\omega}{c} \sqrt{\mu_{efff} \varepsilon_{eff}} \tag{4}$$

To determine ε_{eff} and μ_{eff} another equation for z_{eff} is used:

$$z_{eff} = \sqrt{\frac{\mu_{eff}}{\varepsilon_{eff}}} = \left(\frac{1+\Gamma}{1-\Gamma}\right) \frac{Z^{TL}}{Z_a^{TL}} \tag{5}$$

where Γ is obtained by Nicholson-Ross-Weir approach [37]:

$$\Gamma = k \pm \sqrt{k^2 - 1} \tag{6}$$

$$k = \frac{s_{11}^2 - s_{21}^2 + 1}{2(s_{21})} \tag{7}$$

Parameter extraction is applied to the unit cells consisting of two pairs of identical split-ring resonators (SRRs) realized on two-layer substrate (h_1=0.635 mm, h_2=1.575 mm, ε_{r1}=10.2, ε_{r2}=2.2) and coupled to microstrip line. The vertical via is placed in the middle between top SRRs and bounded to the microstrip conductor and ground plane. The basic configuration (Fig.10(a)) consists of two identical square SRRs on the top of substrate 1 which are coupled with two bottom SRRs on the top of substrate 2. The bottom SRRs have the splits oriented opposite to the above ones. The second unit cell is shown in Fig. 10(b) and consists of SRRs twisted by 90 degrees with respect to basic unit cell. The structure is analyzed using 3D electromagnetic solver Wipl-D Pro v7.1, based on a method of moments (MoM) [38].

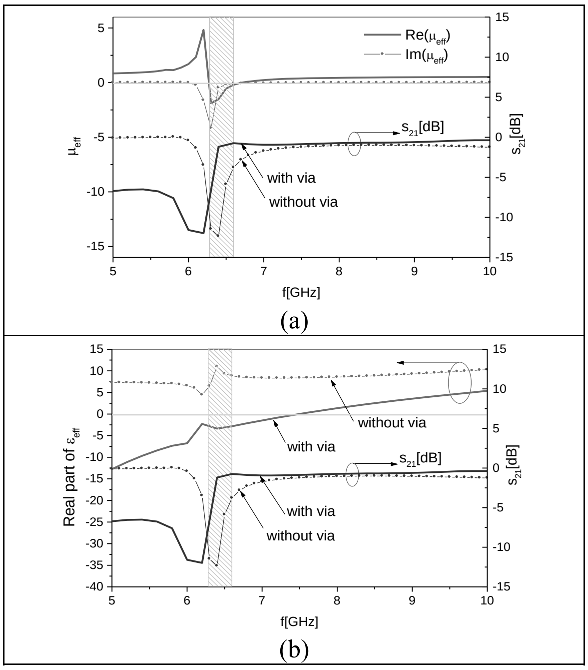


Figure 11. Influence of via for the configuration shown in Fig. 8 (a): (a) the effective μ is unaffected by via, (b) the effective ε becomes positive without via. Region with negative effective μ is denoted by patterned rectangular bar.

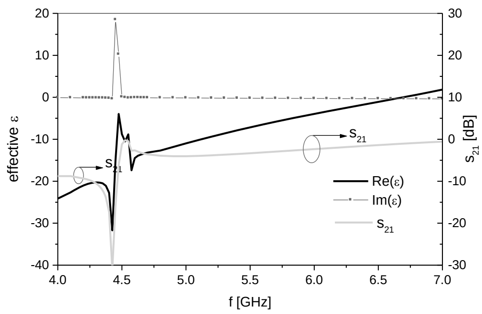


Figure 12. Effective permittivity for the unit cell in Fig. 8 (b).

The parameter extraction procedure is used to investigate the influence of via for the configuration in Fig. 10(a). The results for a unit cell with and without via are shown in Fig. 11. It was shown that the via did not have any effect on extracted effective permeability, but due to the absence of a via, the real part of the effective permittivity becomes positive. Also, it is shown that the structure has a passband only in the region where both effective parameters (their real parts) are negative, i.e. in frequency range 4.4-4.68 GHz.

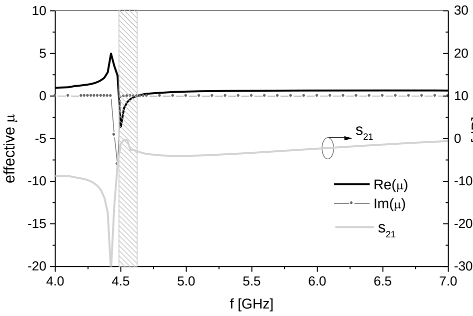


Figure 13. Effective permeability for the unit cell shown in Fig. 8 (b). The rectangular bar denotes frequency range where effective μ is negative.

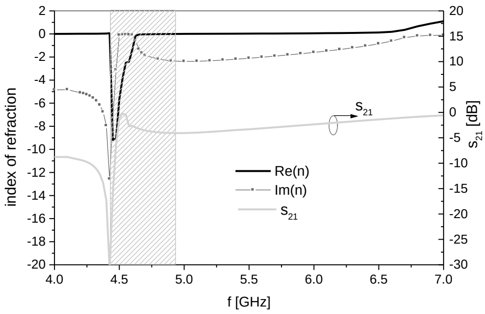


Figure 14. Extracted index of refraction. The rectangular bar denotes the frequency range with negative real part of the refractive index.

The index of refraction is negative in a wider range, for frequencies between 4.33-4.87 GHz, which indicates the existence of region with single negative refractive index.

Veselago showed in his paper [5] that a material with simultaneously negative permeability and permittivity has a negative refractive index. However, this is actually a strong (sufficient) condition. The necessary condition is given by [39]:

$$\varepsilon'|\mu| + \mu'|\varepsilon| < 0 \tag{8}$$

This leads to negative real part of the refractive index. Following from the previous discussion, two types of NIMs can be introduced. Double NIM (DN-NIM) has both $\varepsilon' < 0$ and $\mu' < 0$. A single NIM (SN-NIM) has a negative refractive index with either $\mu' < 0$ or $\varepsilon' < 0$ (but not both). The ratio $|n'|/n''$ is a figure of merit (FOM) and it is always higher for DN-NIMs.

Figs. 12-14 show the extracted effective parameters for the unit cell in Fig. 10(b). The structure exhibits a negative real part of refractive index in the frequency range 4.4-4.9 GHz. The imaginary part of the refractive index is equal to zero in the range 4.5-4.6 GHz which coincides with the range of negative effective permeability. This determines the range of DN-NIM. The index of refraction is positive, but very low (about 0.2) up to 6.7 GHz, at the frequency where the effective permittivity becomes positive (Fig. 14).

Even though the unit cells from Fig. 10 are mutually different, due to SRRs twisted by 90 degrees, the extracted parameters are very similar, even the range where effective permeability is positive and the refractive index is negative.

When split ring resonators are coupled with a microstrip line it is usually done with the configuration from Fig. 10(a), but our simulations and parameter extraction show that both configurations from Fig. 10 exhibit about the same characteristics. The only difference observed is a somewhat increased range of negative permittivity up to 7.28 GHz for the basic configuration. Below this frequency, the refractive index is positive, but very small (about 0.24).

5. COMPACT METAMATERIAL-INSPIRED DEVICES

Split-ring resonators (as described in Section III) originate from [9] and was used in [10,11] with arrays of wires to obtain and demonstrate a negative index of refraction. Split-ring resonators (SRR) and spiral elements are also used as resonator elements in filters, power dividers and couplers [40]-[44]. The SRR consists of two concentric rings with splits on opposite ends. This is a configuration that provides relatively high coupling between the two rings. A simple equivalent circuit is also shown in Fig. 5. These structures provide very efficient ways to obtain miniaturization. Variations on the basic geometry can provide even better miniaturization in for example filters [46] and couplers [44].

5.1 Couplers with Metamaterial Elements

The hybrid coupler of Fig. 15 demonstrates the use of LH and RH unit cells to construct artificial lines with specified phase shifts. The 270° degree line length required in the coupler is replaced by a LH line with phase shift of -90°, which is much shorter. The device is about 3 three times smaller than a conventional design.

Another example is found in [45] using a multilayer low temperature co-fired ceramic (LTCC) technology. Here artificial lines are employed, constructed using quasi-lumped elements. Also in this work [45], a dual-band directional coupler is demonstrated. These devices are about 4 times smaller than conventional design, with good performance.

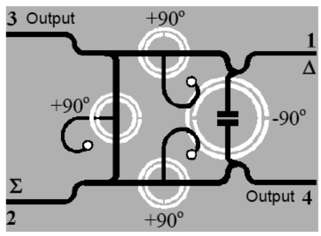


Figure 15: The layout for the hybrid coupler using left-handed (LH) and right-handed (RH) unit cells, adopted from [44].The white rings are on the bottom layer and indicate removed copper.

5.2 Cross-coupled Spiral Resonator (SR) Filter

The filter design (Fig. 16) places zeros in the transmission coefficient at finite frequencies. This is achieved by introducing cross-coupling between the input and output SRs of the filter. The simulated and measured responses are given in Fig. 17. The filter is designed to operate at 2.4 GHz (measured 2.32 GHz) with a Chebyshev response with a fractional bandwidth of 10% (measured 11%). A Taconic substrate with a relative permittivity of 2.2 is used. We found a frequency shift from the predicted response due to tolerances in the manufacturing process. In all filters with such small spacing dimensions between rings (between 100 and 200 microns), a very high precision manufacturing process is required.

It is customary to compare filter dimensions (without feed) as the size in guide wavelengths λ_g. Conventional microstrip filters such as the combline has typical dimensions of $\lambda_g/4 \times \lambda_g/4$ for a fourth order filter.

The dimensions of the cross-coupled fourth order SR filter is $\lambda_g/6.5 \times \lambda_g/6.5$ or 1.6 times smaller than a conventional filter and the introduced transmission zeros in the response result in steeper attenuation slopes than the standard Chebyshev response.

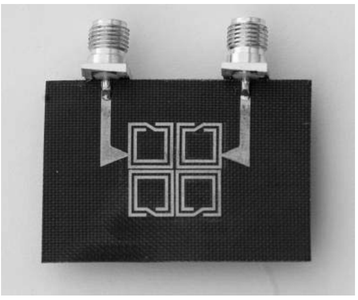


Figure 16: The fourth order cross-coupled SR filter.

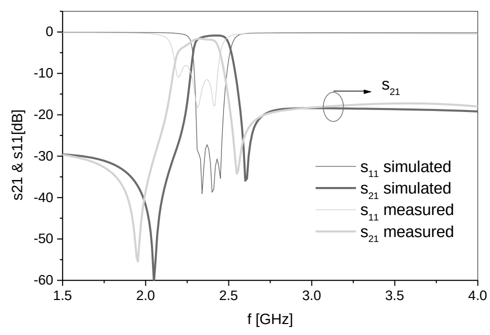


Figure 17: The S-parameters of the simulated and measured filters. The shift in frequency is due the manufacturing process. This filter has very small gaps between rings and requires high-manufacturing precision.

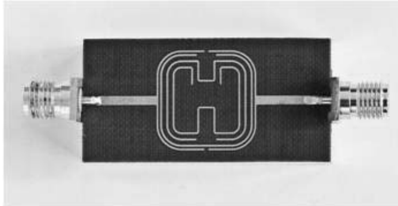


Figure 18: Triple-band SRR resonator with three nested split-ring resonators. Dimensions are w_1=0.6mm, w_2=0.4, w_3=0.4 and g=0.4mm, substrate relative permittivity of 2.2 and substrate thickness 0.76mm.

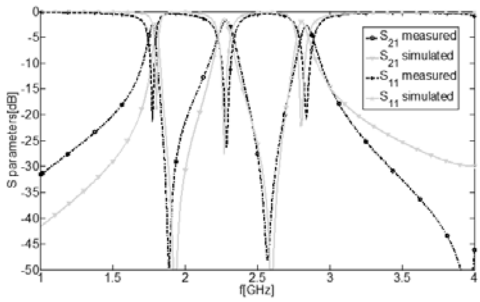


Figure 19: The S-parameters of the simulated (solid lines) and measured (dotted lines) filter. Three passbands with equal spacing are seen. The transmission response demonstrates zeros between passbands.

5.3 Multiband Split-ring Resonators for Filters

Most split-ring resonators have two nested rings (Fig. 5) where the second ring is used to couple strongly to the first and lower the fundamental resonant frequency, thereby providing the miniaturization effect. This produces a spurious pass-band quite close to the main one, and is a liability in some cases.

However, for a dual band or triple-band response, nested resonators are very suitable. Each ring provides an alternative propagation path between the input and output port and can be used to position transmission zeros, thereby constructing separate pass-bands. The possibility to add more rings is limited by the space required to nest the rings. In Fig. 18 we show our composite resonator with three nested split-ring resonators to obtain a triple-band response [46]. For equal mode spacing, the three resonators must have identical resonant frequencies and identical coupling. To fit the inner rings, length corrections are inserted to adjust the resonances. More detail on this type of resonator and design is given in [46].

The simulated and measured response for the filter of Fig. 18 is shown in Fig. 19. The three measured pass-bands are found at 1.775 GHz, 2.283 GHz and 2.873 GHz with insertion losses of 2.6 dB, 1.77 dB and 2.72 dB. The measured unloaded resonator Q-factors are 138, 121 and 114, which are typical for this type of microstrip openring resonators. The composite resonator, which is a third order filter with three passbands, has dimensions $\lambda_g/6.5 \times \lambda_g/6.5$.

CONCLUSION

Metamaterials present a new paradigm in electromagnetics and have attracted great interest in the past ten years. Among metamaterials, negative refractive index materials or left-handed materials have drawn special attention in microwaves. Both resonant and non-resonant types of metamaterials found applications and opened new design strategies in miniaturization, multiband operation, and reconfigurability of microwave devices and antennas. Some new phenomena like zeroth-order resonance, zero phase-shift on arbitrary lengths of LH transmission lines at the transition frequency between RH and LH regions were discovered. From the progress and interest in this field it is clear that the future of metamaterials lies in the field of optics. This is closely linked to advancements in nanotechnology.

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