International Journal of Engineering & Technology, 7 (4.39) (2018) 936-941

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Metamaterial Transmission Line-for Designing a Microstrip Patch Antenna

Awanish Kr Kaushik [1], Anubhav Kumar [2], R. L. Yadava [3]

[1 2 3 4] *Department of Electronics and Communication Engineering*
[1]*G. L. Bajaj Institute of Technology & Management, Greater Noida, G.B.Nagar, Uttar Pradesh, India*
[2] *Rajkumar Goel Institute of Technology for Women, Ghaziabad, India*
[3] *Galgotia's College of Engineering and Technology, Greater Noida, G. B. Nagar, Uttar Pradesh, India*
**Corresponding author E-mail: awanishkkaushik@gmail.com,*

Abstract

In this paper, the fundamental properties, limit and structure of metamaterial express that the "meta-transmission line (meta-TL) is utilized for solace implies metamaterial transmission lines are reasonably homogenous structures, which have properties that don't appear in regular transmission lines. It intertwines all the transmission line structures which have interesting properties not existing in ordinary RH-TL, for instance, LH TL, CRLH TL, SRR \CSRR-stacked TL and further. As diverged from various materials, the Metamaterials are counterfeit metallic structures having meanwhile negative permittivity (ε) and vulnerability (μ), which prompts negative refractive summary. No other mate-rial on the planet demonstrates the above properties like Metamaterial. Because of these irregular properties Metamaterial can change the electric and attractive property of electromagnetic wave encountering it and in light of these reasons when Metamaterial is utilized as a bit of the make of microwave areas and radio wires the required properties can be refreshed.

Keywords: metamaterial, transmission line theory, composite left-handed transmission line.

1. Introduction

This Over the most recent couple of years, an all-encompassing interest showed up in standard masters for the examination of metamaterial. Metamaterials are a class of misleadingly delivered material, in context of irregular or semi discontinuous structures, with remarkable and controllable electromagnetic properties which now and again are missing among standard media. Among various metamaterials, the materials with meanwhile have negative permittivity and penetrability.

The term metamaterial has progressed toward twisting up conventionally a prevalent explanation in electromagnetics and material science get some information about since the start of the 21st century. The importance of a metamaterial developments to some degree depending on the source [1], a few key properties are normally conspicuous.

Above all else, metamaterials are constantly counterfeit composite materials construing that they incorporate two or three stand-out materials managed irrefutably. Being progressively specific, each metamaterial involves fake fuse (each so regularly called "meta-particles"), which can be either spasmodically or self-emphatically managed (indistinct) and are inserted into some dielectric material. Thirdly, metamaterials demonstrate properties found neither in their constituent materials nor in standard basic materials (air conditioning cepting some particular, exceptional and normally fickle substances, for example, plasma).

The metamaterial thought has in like way been stretch out ed to different unmistakable fields of material science, for example, thermodynamics [2], acoustics [3], and mechanics [4].Earlier, it was resolved that one of the key portraying variables of metamaterials is that they give enamoring properties not found in nature.

In nature the permittivity and the vulnerability of most materials are certain. The material with positive permittivity and penetrability are known as right-hand material (RHM). The medium with negative estimations of permittivity ε and vulnerability μ was at first genius presented by Veselago [5]. He named these materials as left-hand materials (LHMs). LHMs can be delineated by some astounding properties that can't be found in nature, including negative refraction, turned around cerenkov radiation, exchanged Doppler influence, etc; [6].

Starting late new metamaterial, LHM pulled a lot of thought, and in [7] it was named unprecedented contrasted with other ten steady jumps forward of 2003. As a term for negative allow tivity and vulnerability materials, "Left-hand material" is generally utilized today, especially in metamaterials subject to transmission line hypothesis and it is moreover the term utilized in this paper, then there are in like way several different names for these materials being used Veselago media, Double negative (DNG) media, Negative Refractive Index (NRI) media Backward-wave (BW) media.

Materials with just a lone negative parameter among permittivity and vulnerability are called single negative (SNG), especially Epson-negative (ENG) or Mu-negative (MNG).Some is-sues worried of the communicating and philosophical parts of metamaterials can be found in [6]. Beginning there, the movement of isotropic LHM examination about has taken after by the theoretical/exploratory improvement of a two-dimensional L-C stacked transmission-line demonstrate [7].

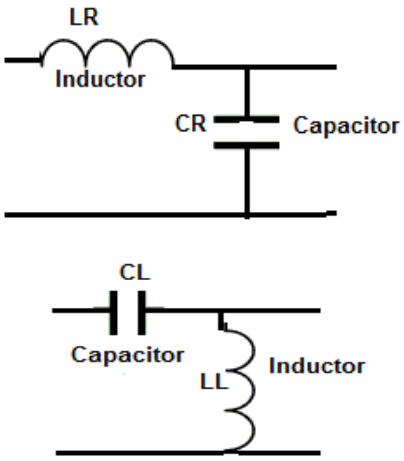


Fig.1: Increment circuit model for (a) a uniform RH transmission line and (b) a uniform LH transmission line

The planar LH transmission line compose was perceived by disconsistently stacking an ordinary transmission line (TL) with lumped arrangement capacitors (CL) and shunt inductors (LR) in a twofold TL (high-pass) structure appeared in Fig. 1, which upheld the retrogressive waves [8]-[9]. The "metamaterial" in this system was deciphered as an interconnected electrical game plan of different parts or focal portions, for example, capacitors, inductors, and resistors, metal wires (or strips), transmission-line pieces, and waveguide packages. The key trademark for this strategy for perceiving "metamaterial" is that they are completely executed by rarely stacking printed transmission line outline works with inductors (L), capacitors (C) and resistors (R). The electromagnetic properties of these metamaterials can be tunable by utilizing variable stacking parts (for example varactors rather than capacitors), as showed up in figure 1.

To take full favorable circumstances of the properties of metamaterials, it requires a framework to tune the electromagnetic reaction of the metamaterial, in an extended recurrence go in as shy of time as could be normal considering the present situation. Models of the indicated dynamic tuning in split ring resonators and transmission line execution join voltage tuned capacitance with barium strontium titanate [10], photograph capacitance tuned semi-guaranteeing gallium arsenide [11] and silicon [12], temperature tuning of vanadium dioxide [13], non-straight power tuning of a varactor [14] and fluid precious stone [15]. The constitutive parameters of the metamaterials are besides associated from straight to nonlinear [16] by utilizing nonlinear substrate.

2. Theoretical Speculation by Viktor Veselago (5)

The chronicled foundation of Metamaterials began in 1967 with the visionary speculation on the nearness of "substances with meanwhile negative estimations of ε and μ" [5] (fourth quadrant of ε-μ space by the Russian physicist Viktor Veselago. In his paper, Vesel-prior called these "substances" left-hand (LH) to express the way in which that they would permit the spread of electromagnetic waves with the electric field, the attractive field, and the stage constant vectors accumulating a left-hand social event of three, differentiated and standard materials where this gathering of three is known to be correct given. Two or three fundamental miracles [5] happening in or in relationship with LH media were anticipated by Veselago:

i. Most required recurrence dispersing of the constitutive parameters
ii. Inversion of Doppler Effect.
iii. Inversion of Vavilov-Cerenkov radiation
iv. Inversion of the limit conditions relating the common portions of the electric and alluring fields at the interface between a traditional/right-gave (RH) medium and a LH medium
v. Inversion of Snell‟s law
vi. Resulting negative refraction at the interface between a RH medium and a LH medium
vii. Change of a point source into a point picture by a LH area
viii. Trade of intermingling and uniqueness impacts in angled and bended central focuses, when the point of convergence is made LH.
ix. Plasmonic verbalizations of the constitutive parameters in full sort LH

3. Electromagnetic Metamaterials

A specific class of Metamaterials includes fake LH (Left-Hand) transmission lines, which might be picked up utilizing arrangement capacitors and parallel related inductors. With this system and utilizing SMDs (surface mounted contraptions), circuits, for example, branch couplers (Lin et al., 2003) and ring couplers (Okabe et al., 2004) working up to a few GHz, have been spoken to. The essential favored perspective of these circuits showed up diversely in connection to the standard ones is the twofold repeat response for any two repeat extent.

Electromagnetic metamaterials might be generally depicted as counterfeit (man-made) attractively homogeneous structures (all things considered made up of a course of action of metals and dielectrics) with remarkable properties not rapidly accessible in nature, They are commonly named as left-hand (LH) materials, having meanwhile negative permittivity (ε) and penetrability (μ), and have permitted novel applications, contemplations, and contraptions to be made. [17]. absolutely, the prefix Meta gathers past or after in Greek, recommending that the medium has properties that rise above those accessible in standard materials, this being the most basic property for metamaterials. Along these lines, a metamaterials carries on certifiable material as in the macintosh roscopic (in a touch of issue) reaction to an electromagnetic field can be depicted by persuading regularly obvious constitutive parameters, to be specific, the permittivity ε and the penetrability μ [17, 18].

Metamaterials, perfectly healthy, are perceived by discontinuously printed sub-wavelength metallic cells which shape a uniframe coincidental structure, the period of which portrays the work-ing repeat band. Metamaterials might be comparably delineated similar to media parameters (electric/charming susceptibilities, permittivity, vulnerability), or as for transmission-line (TL) parameters (inductance/capacitance, impedance/assent, duplication constant/trademark impedance) (18).

4. Material Classification

Since the reaction of a medium to an electromagnetic field is calculated by its characteristics (ε and μ),this approves for the types of a medium depending on the sign of the constitutive parameters, as illustrated in Fig. 2 [19, 20].

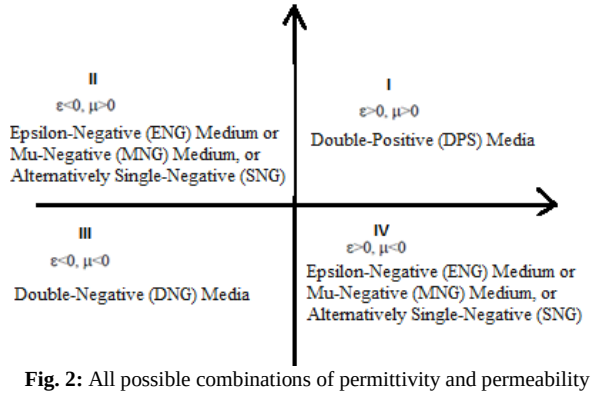


Fig. 2: All possible combinations of permittivity and permeability

Since the reaction of a medium to an electromagnetic field is controlled by its properties (ε and μ), this ponders the depiction of a medium relying on the indication of the constitutive parameters, as outlined in Fig. 2 [19, 20].

Media with both permittivity and penetrability more vital than zero are known as twofold positive (DPS) media. A medium with either permittivity or penetrability under zero is distributed as epsilon-negative (ENG) medium or mu-negative (MNG) medium, only, or of course single-negative (SNG) medium in the two conditions. All the more strangely, media with negative permittivity and vulnerability are called twofold negative (DNG) media, following the past stating. A little while later, several different phrasings have been proposed, for example, left-hand (LH), in reverse wave (BW), and negative-refractive record (NRI) media [19, 20]. Distinctive kinds of metamaterial is showed up in figure 3,

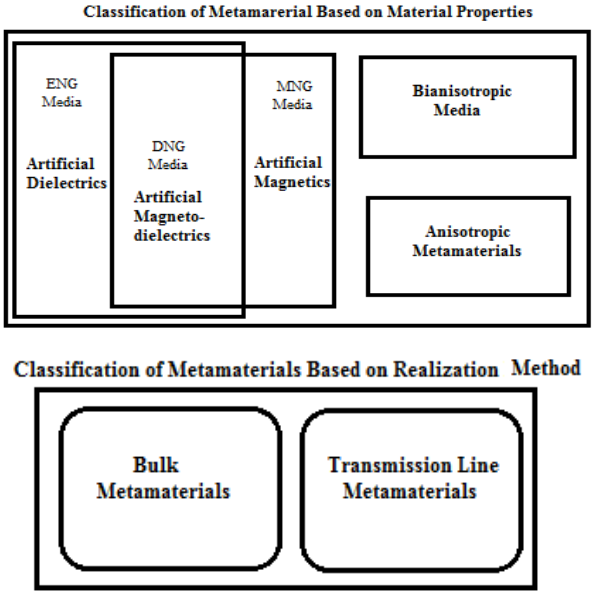


Fig 3: Different types of metamaterials

The spread of electromagnetic waves through a medium at the macintosh roscopic level is managed by Maxwell's conditions, and such a causing relies on the constitutive parameters as takes after. Right when either permittivity or vulnerability is negative, underpins just non-spreading transient modes (the medium murky to flag transmission). In like manner, there can't be essentialness trade through the medium in light of the way that the scene electromagnetic waves bear responsive constriction (reflection, anyway not dispersal) and rot exponentially in ampleness far from the source [21, 22].

5. Transmission-Line Metamaterials

Regardless of the way that twofold negative media were appeared in the mid 2000's to be handy utilizing metamaterials and to have novel properties with several interesting applications, all the proposed metamaterial perceive were very resonated. This property obliges the fittingness of metamaterials for important organizing applications incredibly as the operational data trade limit is extraordinarily confined and the hardships are high. In 2002, the likelihood of transmission line (TL) metamaterials was proposed as a low-dissipating elective decision to customary, mass metamaterials transparently by three particular research bunches [33–24].

Likewise the way that mass metamaterials contain electrically little unions installed (customarily now and again) in a pass on lectric, in TL metamaterials a game plan of TLs goes about as a kind of host medium, while irregularly put lumped or disseminated circuit stacking sections fill the job of the contemplations. In some sense, in reverse wave spread in TL structures was by then a referred to ponder now as Brillouin had contemplated the organize ment capacitance/shunt-inductance circuit appeared in Fig. 4 (an) as a relating circuit appear for in switch wave media in the 1940's [25].

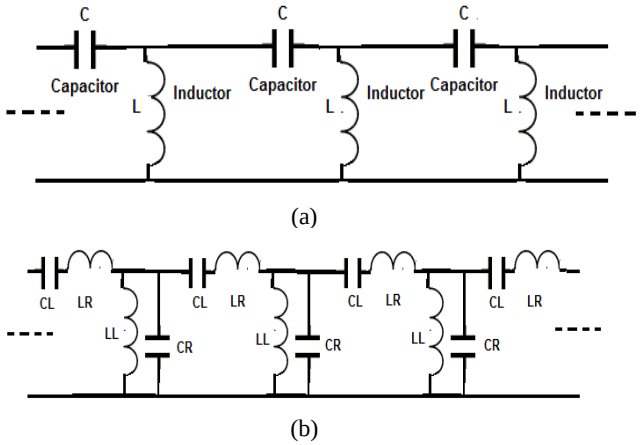


Figure 4: Equivalent circuit model for an ideal (a) and a realistic (b) one-dimensional backward wave medium and an example of a practical microstrip realization corresponding to the latter equivalent circuit (from [27],

The propagation constant and wave impedance of an infinitely intermittent TL structure can be written as

$$\beta = \pm(\omega\sqrt{(1/LC)} \text{ and } Z = \sqrt{(L/C)}, \text{ respectively [26].} \quad (1)$$

Here, C and L define as series impedance (F.m) and shunt admittance (Hm). The phase and group velocities can be written as

$$vp = \omega/\beta = \pm \omega^2\sqrt{LC} \quad (2)$$

$$vg = (\partial\omega)/(\partial\beta) = \mp\omega 2\sqrt{LC}. \quad (3)$$

CRLH TLs can in like manner at that point go about as in reverse wave media at low frequencies where the effect of the arrangement inductor LR and shunt capacitor CR is nearly nothing and the circuit of Fig. 4 (b) is comparatively reduced to the circuit of Fig. 4 (a). On the other hand, common forward wave modes are strengthened at higher frequencies as LR and CR arrange over LL and CL. Fundamentally, the CRLH TLs are commonly recognized utilizing microstrip lines so the required circuit sections are perceived as scattered portions, explicitly the arrangement capacitor as between computerized capacitor and the shunt inductor as a shunt stub inductor, e.g., [21– 24, 27]. Transmission-line metamaterials (or metamaterial transmission lines) are fake transmission lines [40] that involve a host (conventional) transmission line stacked with responsive parts, the last giving higher structure adaptability interestingly with customary lines [28].

6. Application of the Transmission-Line Theory to Metamaterials

Major application areas of metamaterials

- Microwave Invisibility Cloaks
- Invisible Submarines
- Revolutionary Electronics
- Negative Refractive-Index Lenses
- Waveguides and Microwave Components
- Compact and Efficient Antennas

The revealed strategy for Application of the Transmission-Line Theory to Metamaterials starts from the way that Maxwell's conditions with plane-wave spread in homogeneous and isotropic media have an undefined edge to the conditions de-lineating TEM causing on a transmission line got from circuit speculation, known as the telegrapher conditions. Thusly, such a relationship permits the

arrangement and shunt parts of the striking advance circuit model of a transmission line to be identified with the constitutive parameters of a medium (showing a near spread qualities) by mapping the telegrapher conditions to Maxwell's conditions [29– 30].

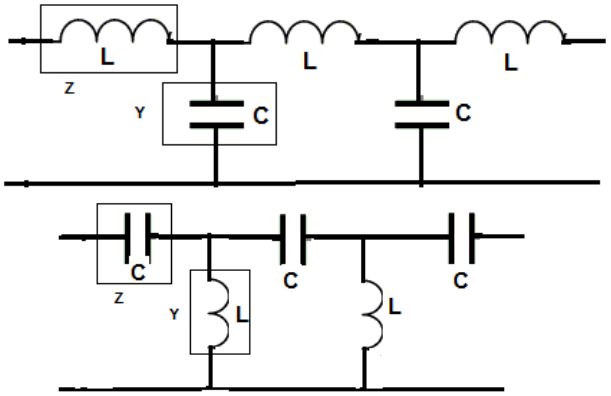


Fig. 5: Equivalent circuit model of a transmission line. **a** Conventional or RH transmission line. **b** Dual or LH transmission line

From figure the value of per-unit-length series impedance (Z) (Ω/m) and shunt admittance (Y) (S/m) is respectively-

$$Z = Zs/L = j\omega\mu, \quad (4)$$

$$Y = Yp/L = j\omega\varepsilon, \quad (5)$$

Where Lis the unit cell length (the period). Accordingly, in conventional RH media, the mapping yields

$$\mu = L' = L/l, \quad (6)$$

$$\varepsilon = C' = C/l, \quad (7)$$

Where L' and C' are the per-unit-length course of action inductance (H/m) and shunt capacitance (F/m), exclusively, while L and C address the per-unit-cell arrangement inductance (H) and shunt capacitance (F), independently. The ensuing without a doubt saw star portional circuit is demonstrated schematically in Fig. 5 (a), proliferation is forward with an engendering consistent and a trademark impedance given by

$$\beta R = \omega \sqrt{(L'C')}, \quad (8)$$

$$ZcR = \sqrt{(L'/C')}, \quad (9)$$

Individually, in the transmission-line approach of metamaterials the past settled likeness has been extended to the following (colorful) mixes of the constitutive parameters depending upon their sign. Along these lines, for a LH medium, the arrangement inductance and the shunt capacitance should finish up negative. Since from an impedance perspective a negative inductance/capacitance may be translated as a positive capacitance/inductance [29], a venturing stool organize as the one depicted in Fig. 5 (b)a with arrangement related capacitors and shunt-related inductors reinforces the engendering of in reverse waves . Such a framework is known as the double of the com-illustration circuit of a RH transmission line. The mapping in this double framework yields

$$\mu = -1 / \omega 2C' = -1 / \omega 2Cl \quad (10)$$

$$\varepsilon = -1/ \omega 2L' = -1 / \omega 2Ll \quad (11)$$

Where C' and L' are finally the time-unit-length series capacitance (F ・m) and shunt inductance (H ・m), respectively, while C and L stand for the per-unit-cell series capacitance (F) and shunt inductance (H), respectively. The corresponding propagation constant and characteristic impedance now can be defined as

$$\beta L = -1/\omega \sqrt{(L'C')}, \quad (12)$$

$$ZcL = \sqrt{(L'/ C')}, \quad (13)$$

Exclusively. Reverse to a dissipating less RH line, a LH transmission line is normally dispersive basically in light of the way that its proliferation steady is authentically not an immediate capacity of recurrence. It should similarly be underlined that it is authentic just in the long wavelength, where the period is extensively humbler than the guided Wavelength

$$\lambda g = 2\pi|\beta| , \quad (14)$$

7. Metamaterial-Based Resonators

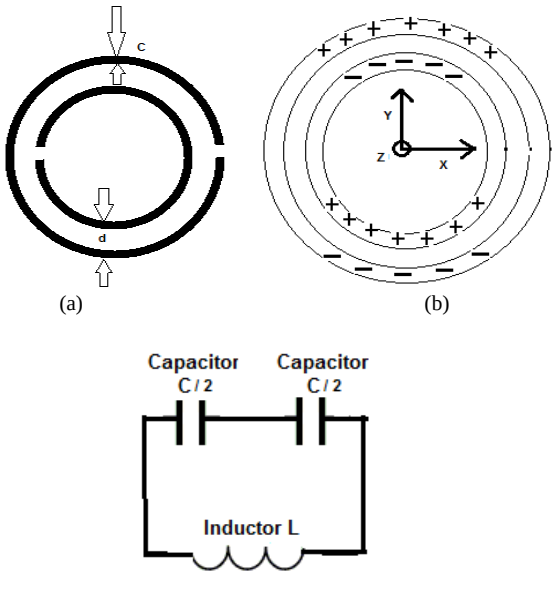
This bit isolates two or three resonator topologies as split rings utilized for the amalgamation of transmission-line metamaterials, or RF/microwave devices pushed by metamaterials. These resonators are reliably known as metamaterial-based resonators or basically metamaterial resonators. When in doubt, negative penetrability/permittivity structures might be executed by procedures for topologies not the proportional as that of the vital SRR/CSRR. Different electrically insignificant planar resonators have been spoken to in the piece [31, 32, 33], and they can be accumulated by two or three criteria. Every last one of them have in like way the running with highlights, Sub wavelength, and in like way they may be suggested as semi-lumped or lumped resonators.

• Closed, as in resonation is incited by external electromagnetic fields.
• Planar, being totally great with planar development.
• Symmetric, so when the topology is partitioned along its symmetry plane, one of the parts is the indistinguishable portrayal of the other an expansive bit of (a plane of symmetry goes about as a mirror).

In any case, every single one of the topologies indicate diverse unconventionalities that make them steady or increasingly fitting in a few conditions [31, 35]. It is ordinary here that the level of the resonators is on a scale liberally shorter than the wavelength, with the true objective that a typical motivator for the fields might be sensibly depicted. In like way, the resonators should be lit up by outside uniform time-differentiating electric or attractive fields with the standard sinusoidal, or consonant, time dependence.

7.1. Split-Ring Resonator (SRR)

The important medium proposed in [32] incorporates a com-plex mix of metal wires and Split Ring Resonators (SRRs) [31], which are a few concentric annular rings with spilts in them at inverse finishes. An outside time-fluctuating attractive field associ-ated parallel to the molecule hub affects turning current in the rings, which passes on SRR's own one of a kind advancement to overhaul or confine the episode field. SRR carries on as a LC full tank by balance of the appropriated capacitance between concentric rings and all things considered rings inductance. At frequencies underneath thunderous recurrence the one of a kind bit of attractive penetrability of SRR winds up being significant (positive) and goes to negative characteristics at frequencies higher than the full one. This negative vulnerability can be utilized with negative dielectric unfaltering of another structure (i.e., group of metallic shafts) to pass on negative refractive file materials [33] [34]. The Circular topology (Fig 6a), Fundamental resonation: presentation of the polarization fields (Fig 6b), and Equivalent cir-cuit model of a SRR (Fig 6a) is showed up in figure 6.



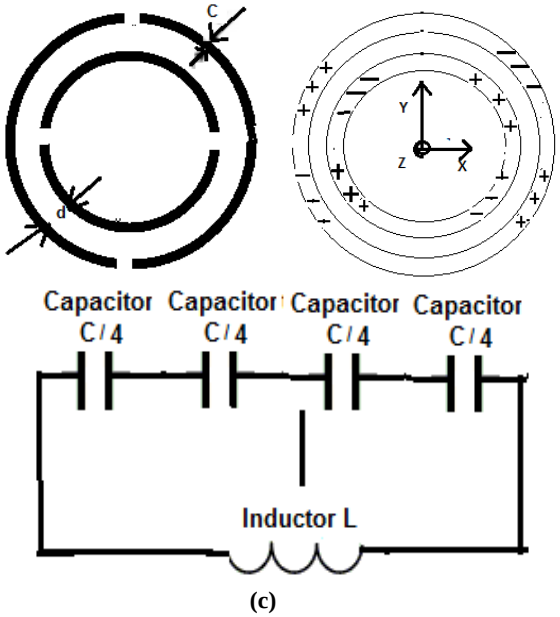
(a) (b)

(c)

Fig. 6 Symmetric split-ring resonator (SRR). **a** Circular topology. **b** Fundamental resonance: orientation of the polarization fields, (c) Equivalent circuit model of an SRR

7.2- Double-Slit Split-Ring Resonator (DS-SRR)

The twofold opening split-ring resonator (DS-SRR) is gotten from the fundamental topology of the SRR by showing an extra cut in each ring and by turning one of the rings 90◦, as appeared in Fig. 7 (a) [35]. This molecule is bisymmetric, which induces that it has two symmetrical symmetry planes, coming about invariant by inversion. As Fig. 7 (b), the two symmetry planes bear on as electric dividers at reverberation and, in parity of their symmetry, the nearness of a net electric dipole is neutralized. Subsequently, the key reverberation of the DS-SRR can't be electrically invigorated with uniform fields. Between estingly with the vital SRR, by applying a quasistatic examina-tion, the DS-SRR has about a practically identical inductance in any case four time's tinier capacitance. The decrease in the all out capacitance ascends out of the arrangement relationship of the four capacitances, every last one of them relating to every quadrant (see Fig. 7 (b)). Hence, resonance recurrence of the DS-SRR is about twice that of the SRR, and the electrical size also (see Fig. 7 (c)).

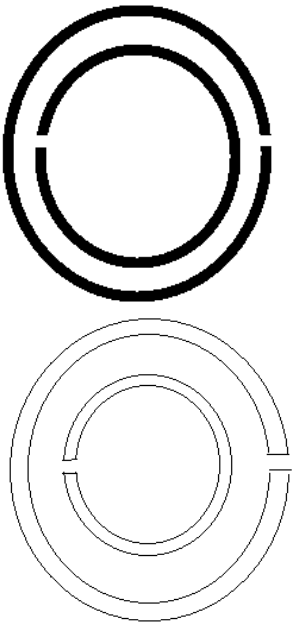


(c)

Fig. 7: Bisymmetric double-slit split-ring resonator (DS-SRR). **a** Circular topology. **b** Fundamental resonance: orientation of the polarization fields, **(c)** Equivalent circuit model of a DS-SRR.

7.3. Complementary Resonators

The corresponding accomplices of the resonators examined in the principle sub-areas are introduced here. As is striking, two correlative structures are portrayed as those where one is acquired from the other by ex-changing the holes (spaces) for the strong (metallic) parts of a plane [36]. Thusly, while comparing structures are obliged, they shape a solitary unbounded strong screen without any spreads. As endorsed in the arrangement [37], to stay away from indefinite quality, a resonator made of electrically planning strips is recommended here to as a strip resonator, anyway a resonator picked up by cutting openings in a metallic surface as a space resonator. With the end goal of isolating the lead of resonators as openings, the contemplations of duality and complementarily are gathered as a significant part of the time [36, 37].



(a) (b)

Fig. 8: Complementary resonators. **a** SRR and **b** CSRR

8. Conclusions

After examination the all out delineation of metamaterial clearly the metamaterial transmission lines are one-estimation structures. Their shows can be generally isolated by the circuit models, and the relationship between them. There are different livelihoods of metamaterial transmission lines in perspective of their impressive execution. Some ordinary applications, for example, broke wave radio wire, resonators, diplexers and power dividers are exhibited. Metamaterial transmission lines will discover a reliably extending number of jobs of microwave sections in future. This paper rotate around Theoretical Speculation of metamaterials by Viktor Veselago, Electromagnetic Metamaterials, Principles to appreciate the LH-TL with usage of the Transmission-Line Theory to Metamaterials, joins Metamaterial-Based Resonators.

References

[1] C. Caloz, T. Itoh, Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications (Wiley, New York, 2005)

[2] K. P. Vemuri, F. M. Canbazoglu, and P. R. Bandaru, “Guiding conductive heat flux through thermal metamaterials,” *Appl. Phys. Lett.*, vol. 105, p. 193904, 2014.

[3] J. Li and C. T. Chan, “Double-negative acoustic metamaterial,” *Phys. Rev. E*, vol. 70, p. 055602, 2004.

[4] Z. G. Nicolao and A. E. Motter., “Mechanical metamaterials with negative compressibility transitions,” *Nat. Mater.*, vol. 11, pp. 608–613, 2012.

[5] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ", Soviet Physics Uspekhi, Vol. 10, pp. 509-514, January-February 1968.

[6] A Sihvola, "Metamaterials in electromagnetics (invited review)", metamaterials, vol 1 no 1, pp 2-11, 2007

[7] A. Grbic and G.V. Eleftheriades, "Sub-wavelength focusing using a negative-refractive-index transmission-line lens," IEEE Antennas and Wireless Propagation Letters, vol. 2, pp. 186-189, 2003.

[8] A.K. Iyer, P.C. Kremer and G.V. Eleftheriades, "Experimental and theoretical verification of focusing in a large, periodically loaded transmission line negative refractive index metamaterial." Optics Express 11, pp. 696-708, April 07, 2003.

[9] A. Grbic and G.V. Eleftheriades, "Growing Evanescent Waves in Negative-Refractive-Index Transmission-Line Media," Applied Physics Letters, vol. 82, no. 12, pp. 1815-1817, March 24, 2003.

[10] T.H. Hand and S.A. Cummer, "Frequency tuning electromagnetic metamaterial using ferroelectric loaded split rings," J. Appl. Phys. 103, 066105, 2008 .

[11] K.A. Boulais, D.W. Rule, S. Simmons, F. Santiago, V. Gehman, K. Long, and A. Rayms-Keller, "Tunable split-ring resonator for metamaterials using photocapacitance of semi-insulating GaAs," Appl. Phys. Lett. 93, 043518, 2008.

[12] A. Degiron, J.J. Mock, and D.R. Smith, "Modulating and tuning the response of metamaterials at the unit cell level," Optics Express 15, 1115, 2007.

[13] T. Driscoll, et al., "Dynamic tuning of an infrared hybrid-metamaterial resonance using vanadium dioxide," Appl. Phys. Lett. 93, 024101 ,2008

[14] I.V. Shadrivov, S.K. Morrison, and Y.S. Kivshar, "Tunable split-ring resonators for nonlinear negative-index metamaterials," Optics Express 14, 9344, 2006.

[15] F. Zhang, Q. Zhao, L. Kang, D. P. Gaillot, X. Zhao, J. Zhou, D. Lippens, "Magnetic control of negative permeability metamaterials based on liquid crystals", Appl. Phys. Lett. 92, pp. 193104, 2008.

[16] A A Zharov, I V Shadrivov, and Yu.S.Kivshar, "Nonlinear Properties of Left-Handed Metamaterials," Phys. Rev. Lett. 91, 037401 ,2003

[17] C. Caloz, T. Itoh, Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications (Wiley, New York, 2005)

[18] N. Engheta, R.W. Ziolkowski, Metamaterials: Physics and Engineering Explorations (Wiley, New York, 2006)

[19] C. Caloz, T. Itoh, Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications (Wiley, New York, 2005)

[20] N. Engheta, R.W. Ziolkowski, Metamaterials: Physics and Engineering Explorations (Wiley, New York, 2006)

[21] G.V. Eleftheriades, K.G. Balmain, Negative-Refraction Metamaterials: Fundamental Principles and Applications (Wiley, New York, 2005)

[22] S.Ramo, J.R.Whinnery, T.VanDuzer, Fields and Waves in Communication Electronics (Wiley, New York, 1965)

[23] A. A. Oliner, "A periodic-structure negative-refractive-index medium without resonant elements," in *Proc. IEEE APS/URSI International Symposium Digest*, San Antonio, TX, USA, June 2002, p. 41.

[24] C. Caloz and T. Itoh, "Application of the transmission line theory of left handed (LH) materials to the realization of a microstrip "LH line"," in *Proc. IEEE Antennas and Propagation Society International Symposium*, vol. 2, San Antonio, TX, USA, June 2002, pp. 412–415 vol.2.

[25] L. Brillouin, *Wave Propagation in Periodic Structures*. Hoboken, New Jersey, USA: McGraw–Hill, 1946.

[26] J.B. Pendry, A.J. Holden,D.J.Robbins,W.J. Stewart,Magnetism from conductors and enhanced nonlinear phenomena. IEEE Trans. Microw. Theory Tech. **47**(11), 2075–2084 (1999).

[27] A. Sanada, C. Caloz, and T. Itoh, "Characteristics of the composite right/left-handed transmission lines," *IEEE Microw. Compon. Lett*, vol. 14, no. 2, pp. 68–70, 2004.

[28] F. Martín, Artificial Transmission Lines for RF and Microwave Applications (Wiley, New York, 2015)

[29] N. Engheta, R.W. Ziolkowski, Metamaterials: Physics and Engineering Explorations (Wiley, New York, 2006)

[30] R. Marqués, F. Martín, M. Sorolla, Metamaterials with Negative Parameters: Theory, Design and Microwave Applications (Wiley, New York, 2008)

[31] R. Marqués, F. Martín, M. Sorolla, *Metamaterials with Negative Parameters: Theory, Design and Microwave Applications* (Wiley, New York, 2008)

[32] L. Solymar, E. Shamonina,*Waves in Metamaterials* (OxfordUniversity Press, NewYork, 2009)

[33] F. Martín, *Artificial Transmission Lines for RF and Microwave Applications* (Wiley, New York, 2015)

[34] D.R. Smith, W.J. Padilla, D.C. Vier, S.C. Nemat-Nasser, S. Schultz, Composite medium with simultaneously negative permeability and permittivity. Phys. Rev. Lett. **84**(18), 4184–4187 (2000)

[35] R. Marqués, J. Baena, J. Martel, F.Medina, F. Falcone,M. Sorolla, F.Martín, Novel small resonant electromagnetic particles for metamaterial and filter design, in *International Conference on Electromagnetics in Advanced Applications (ICEAA '03)* (Torino, Italy, 2003). pp. 439–442

[36] H. Booker, Slot aerials and their relation to complementary wire aerials (Babinet's principle). J. IEE Part IIIA **93**(4), 620–626 (1946)

[37] R. King, G.H. Owyang, Complementarity in the study of transmission lines. IEEE Trans. Microw. Theory Tech. **8**(2), 172–181 (1960).