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Metamaterials-A New Era of Artificial Materials with Extraordinary Properties

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Abstract —
This review paper based on the utility of metamaterials in the various electronics field. In this paper we described the brief historical background of metamaterials and their classification. Then further we discussed the different structure approaches of metamaterials and their advantages. After that we have given major achievements of metamaterials application and offer an analysis of the future outlook for this field.

KEY WORDS-

Metamaterials (MTMs), Left handed media (LHM), Split ring resonator (SRR), Single negative material (SNG), Double negative material (DNG), Metactronics and Electromagnetic band gap (EBG).

1. INTRODUCTION

Metamaterials were first known as LHM (left handed media).the concept of LHM was proposed by Veselago in 1968 [1]. The term of metamaterials come in the existence of year 2001 by R.M walser. He has proposed the definition of metamaterials following as-Metamaterials are defined as macroscopic composites having a man-made, three dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to a specific excitation [2].After the various definitions suggested and describe the term metamaterial. Some of them are giving below.Metamaterials are typically man-made and have properties that are not found in nature [3].Metamaterials are artificially engineered structures that have properties not attainable with naturally occurring materials [4].Metamaterials are artificial media structured on a size scale smaller than the wavelength of external stimuli [5]. All above definition realized that metamaterial is an artificial material with unusual electromagnetic properties which is not readily available in nature. The most unusual property achievable in MTMs is probably negative refraction which is achieved when both the permittivity and permeability of a medium are negative [1]. First revolution with LHM noticed in year 1996. When the arrays of thin parallel conducting wires whose permittivity was negative below the plasma frequency discovered by Pendry [6], [7]. In 1999 he discovered the array of metallic rings called split ring resonators whose permittivity was negative just above the resonant [8]. In the year of May 2000 physicist David smith proposed combine parallel thin wire and SRR composite material which simultaneously exhibit negative permittivity and permeability over a finite frequency band and created the first LHM [9]. It is also known as backward-wave media [10]. In October 2000 Pendry invented the super lens for such lenses able to refocus wave far beyond the well known diffraction limit [11].The second revolution in metamaterials came in

2005 when the gradient refractive index medium was realized to bend electromagnetic waves which were discovered by smith [12]. In 2006 the optical transformation theory was proposed by Schurig et al., make visible cloak to control the propagation of electromagnetic waves using the metamaterials [13], [14]. In the year of 2007 the professor Engheta gave a new concept of future electronics which is based on nano scale also called metactronics [15].Today scientist and engineers all over the world are finding the new exciting features of metamaterials. In recent years we have witnessed number of design and application of various types of metamaterials. The modern trends in metamaterial applications are more focusing on the nano structure photonic circuitry (metactronics) and power harvesting.

1. METAMATERIALS CLASSIFICATION AND THEIR DESIGN STRUCTURES

Metamaterials are artificial materials characterized by constitutive parameter generally not found in nature. In the designing of

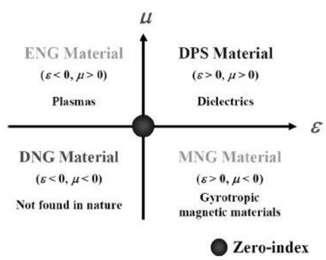


Fig.1. Classification of metamaterials by the real parts of their constitutive parameters, i.e., their permittivity and permeability metamaterials most of material properties have to be realized together and these properties are defined by the constitutive parameters permittivity (ε) and permeability (μ) [16], [17], [18].So on the basis of ε and μ, material can be classified according to diagram shown in figure 1.

a. Zero Index Material-

When both permittivity and permeability are zero, which fall at the origin of Figure 1**,** have been termed zero-index materials [19].

DPS Material-

The material in the first quadrant have positive real value of permittivity and permeability and they know as double positive (DPS). These materials allow right handed propagation so they also known as right handed media (RHM). All natural dielectric fall in this category. DPS or RHM also used in designing of metamaterials [16], [17], [18].

b. ε Negative (ENG) Material and its structure-

The material in the second quadrant has negative permittivity and positive permeability such material known as ε negative (ENG). When this property realized in metamaterial design it is known as ENG metamaterial. It is the metal thin wire structure which shown in figure 2. This structure consists of thin parallel conducting wires. When excitation electric field E is parallel to the axis of the wires so as induce a current along them and generate equivalent electric dipole moments.

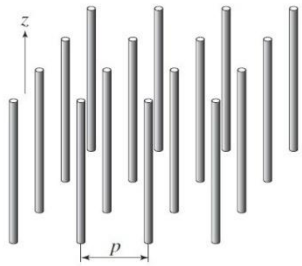


Fig.2. Thin-wire (TW) structure exhibiting negative ε/positive μ

This MTM is exhibiting plasma like permittivity there by providing negative value below the plasma frequency. The thin wire behaves as an effective plasma medium described by the frequency dispersive Drude model [6], [7], [17], [18].

$$\varepsilon_r = 1 - \frac{f_{ep}^{\ 2}}{f^2 + i\gamma_e \frac{f}{2\pi}}$$

Subscript r refers to relative values, where f_{ep} is the electric plasma frequency and γ_e the electric damping factor. Generalization of the wire medium obtained by loading the wires with lumped elements has also been investigated in [20] further detailed analysis revealed that the wire medium exhibits strong spatial dispersion [21].

c. µ Negative (MNG) Material and its structure-

The material in the fourth quadrant has negative permeability and positive permittivity, known as µ negative (MNG) material. When this property is realized in metamaterial design it is known as µ negative metamaterial. It is the metal split ring resonator structure (SRR) shown in figure 3. It was first proposed in [8]. It is basically a sub wavelength magnetic resonator made of inductive metallic rings loaded with capacitive gaps if the excitation magnetic field H is perpendicular to the plane of the rings, so as to induce circulating current in the rings, which in turn give rise to a magnetic dipole moment.

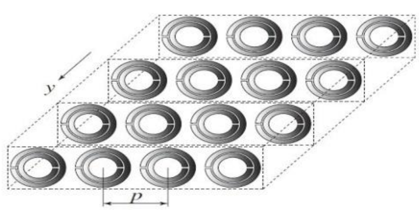


Fig.3. Split-ring resonator (SRR) structure exhibiting positive ε/negative μ

This MTM structure obey frequency dispersive Lorentz model with possible negative values just above the resonant frequency.

$$\mu_r = 1 - \frac{f_{mp}^{\ 2} - f_{mo}^{\ 2}}{f^2 - f_{mo}^{\ 2} + i\gamma_m \frac{f}{2\pi}}$$

Subscript r refer to relative values, γ_m is the magnetic damping factor f_{mo} is magnetic resonant frequency, f_{mp} is magnetic plasma frequency [17], [18].

Coupling effect between SRR in an array have been investigated [22] and magneto electric coupling occurring in these structure have been highlighted and described in [23], [24]. Spiral resonator has been proposed in [25] to lower the resonant frequency, thus decreasing the electrical size of the cells at resonance. ε negative and μ -negative materials may be collectively named single-negative (SNG) material [17].

d. Double negative (DNG) material and its structures

It is very famous class of metamaterials. This class of material lies in the third quadrant and has the negative permittivity and permeability so they known as double negative (DNG). These material allow backward wave propagation so they also know as left handed media (LHM) [1], backward-wave media (BW media) [10], and double-negative (DNG) materials.

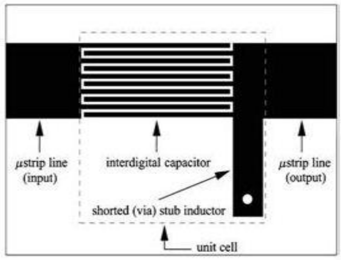
The first reported LHM obtain by combining the metal thin wire (ENG material) and spilt ring resonator (MNG material) [9]. This structure exhibits LH behaviour for one direction of propagation (1D LHM). An improved 2D version of LHM [26] shows in figure 4 which allowed the first experimental verification of negative refraction [27].

Fig. 4. 2D LHM [27]

So many variants of LHM structure have been reported. Some of them are discussed below and their structures given in figure 5. Ω shaped metallic structure is new kind of LHM has been proposed in [28]. It is combined electric magnetic resonator. S shaped resonator has been proposed in [29]. This structure has no rods issue which is very significant advantage in waveguide measurement.

(i)

(ii)



(iii)

(IV)

Fig.5. (i) unit cell on Ω pattern [28] (ii) unit cell on S pattern (iii) TL based unit cell of 1D LHM [37] (iv) mushroom based 2D LHM.

Fishnet structure is a short wire pairs with continuous wires structure firstly reported in [30] . Its resulting structure and variation have been analysed in [31].

These all structures are based on metallic inclusion approach which has disadvantage of high losses as the frequency increases towards millimetre. To overcome of this problem a new LHM structure has been proposed which is based on dielectric inclusion. It is a combination of two lattices of high permittivity dielectric spherical particles [32]. It exhibit lower loss than metallic ones.

After these structures TL (transmission line) based approach come in focus. TL based LHM do not rely on the resonance phenomenon so they exhibit low loss and wide band behavior compared to resonant counterpart [33]. TL based LHM structure has been proposed at the same time by three groups [34], [35], [36]. These structures were mainly concerned with planner 1D [37] or 2D [38] structure but recently some possible volumetric 3D LHM have been proposed and experimentally tested [39], [40], [41].

The design and optimization of the LHM have been an active area of research because the shape of rings ,their effective radii, the radii of wire, the width of metallization govern their resonant and plasma frequencies which are directly related to the bandwidth where negative value occur.

2. METAMATERIALS APPLICATION AND ACHIEVEMENTS

Due to the exciting and unusual features, metamaterials have found and are finding a lot of application or potential application. Some of metamaterial achievements are giving below.

A. Super lens-

A super lens or perfect lens is an optical lens with resolution capabilities that go substantially beyond ordinary lens. In October 2000 Pendry invented the term perfect lens (LHM-lens) for such lenses are able to refocus wave for beyond the well Known diffraction limit [11] [42]. It is widely used in super resolution medical imaging, optical imaging, and non destructive detection. The first super lens in the microwave regime was realized in 2004 [43], which demonstrated resolution three times better than the diffraction limit. Later fang et al. proposed the first optical super lens using thin silver film [44] which break the diffraction limit and produce super resolution images [45]. In 2010 a nano wire array proto type described as a three dimensional metamaterial nano lens [46].

B. Metamaterial cloaking-

The successful demonstration of invisible cloaks has been done experimentally in microwave regime [14] [47]. Transformation optics is a novel method for the design of invisibility cloak-a material that can be used to hide the object from detection [13], [14]. This approach gives the opportunities for the control of electromagnetic waves. In 2009 a group of researchers announced cloaking at optical frequencies. In this case the cloaking frequency was centered at 1500 nm (in infrared range) [48], [49]. The metamaterial acoustic cloak is designed to hide objects submerged in water. The acoustic cloak demonstrated effectiveness for the sound wavelength of 40 kHz to 80 kHz in 2011[50], [51], [52]. The main application of cloaking device is in stealth technology.

C. Metamaterial antennas-

Metamaterial antennas are a class of antennas that use metamaterial to manipulate the size, efficiency, bandwidth and directivity of antenna. Metamaterial permits smaller antenna element that cover wide range of frequency . Antenna based on metamaterial coating to enhance the radiation and matching properties of electrically small electric and magnetic dipole antenna[53], [54]. The power radiated by a small antenna can be increased through the application of DNG metamaterial [55].metamaterial antenna are commercially used in cell phones [56]. In 2005 a patch antenna with metamaterial cover was proposed that enhanced directivity. According to the numerical results, the antenna showed significant improvement in directivity, compared to conventional patch antennae. This was cited in 2007 for an efficient design of directive patch antennas in mobile communications using metamaterials. Wireless Communication, satellite communication, air planes are some other applications of metamaterial antennas. Metamaterials and their antenna application is very interesting and developing research area in upcoming years [57], [58].

3. FUTURE OUTLOOK OF METAMATERIAL

A. Seismic metamaterial-

Seismic metamaterial are metamaterials which are designed to counteract the adverse effects of seismic waves on artificial structure which exist on or near the surface of the earth. As 2009 seismic metamaterial were still in the development stage. Seismic metamaterial have the ability to manipulate seismic waves which are created by earthquake. The idea is proposed that if the metamaterial used as ring around a building foundation then there have possibility that it diverts the most destructive seismic waves around the entire building [59], [60].

B. Tunable metamaterial-

Regular metamaterial only respond to one frequency or frequency band but tannable metamaterial has the ability to arbitrary adjust frequency change in the refractive index. Electromagnetic band gap (EBG), also known as photonic band gap (PBG), and negative refractive index material (NIM) are the ongoing research area of this domain. Researchers are developing a new metamaterial design which allows certain properties to be tuned with external light source and will provide the switching property. The device can switch from a normal flat mirror to a focusing/defocusing mirror without changing its shape [61], [62].

C. Metactronics (metamaterial inspired nanoelctronics)-

Metactronics is metamaterial based approach to designing future electronics on a nano scale. This concept has given by the professor Nader Engheta in 2007. In this concept Engheta is exploiting the optical properties of metamaterial for designing electronics circuit. Nano particles will play the role of lumped nanocircuit elements such as nanocapacitors, nanoresisters and nanoinductors. These optical nano electronics will work with light instead of electron transport [15].

D. Power harvesting metamaterial-

Metamaterials are well-suited for electromagnetic power harvesting. Power harvesting devices convert one type of energy to another. Researchers say the power-harvesting metamaterial could potentially be built into a cell phone, allowing the phone to recharge wirelessly while not in use. This feature could, in principle, allow people living in locations without ready access to a conventional power outlet to harvest energy from a nearby cell phone tower instead. Improve the energy efficiency of appliances by wirelessly recovering power that is now lost during use [63], [64].

4. Conclusion

All experimental and theoretical demonstration of metamaterials shows that Metamaterials have become an extremely fertile research area. In the last 12 years we have seen many revolution and achievements in this discipline such as negative refraction, super lens and invisible cloak. Now super resolution imaging, the nanostructure metamaterials or metactronics, light harvesting for improved solar cell technology and power harvesting are the modern trend of metamaterial applications. We expect that many other fascinating discoveries and application will be found in future and explore the hidden world of metamaterials

References:

1. V. G. Veselago, “The electrodynamics of substances with simultaneously negative values of epsilon and mu”. Soviet Physics Uspekhi, vol. 10, no. 4, pp. 509–514, 1968.
2. R. M. Walser, “Electromagnetic metamaterials,” Proc. SPIE, vol. 4467, pp. 1-15, 2001.
3. V. M. Shalaev, “Optical negative-index metamaterials,” Nature Photonics, vol. 1, pp. 41-48, 2007.
4. J. Valentine, S. Zhang, T. Zentgraf, E. Ulin-Avila, D. A. Genov, G. Bartal and X. Zhang,“Threedimensional optical metamaterial with a negative refractive index”, Nature, vol. 455, pp. 376-379, 2008.
5. Nikolay I. Zheluder, “The Road Ahead for Metamaterials,” science, vol. 328, no. 5978, pp. 582-583, 2010.
6. J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, “Extremely low frequency plasmons in metallic mesostructures,” Physical Review Letters, vol. 76, no. 25, pp. 4773–4776, 1996.
7. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, “Low frequency plasmons in thin-wire structures,” J. Phys.: Condens. Matter, vol. 10, pp. 4785–4809, 1998.
8. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart. “Magnetism from conductors and enhanced nonlinear phenomena,” IEEE Trans. Micr. Theory. Tech., vol. 47,no. 11, pp. 2075–1084, Nov. 1999.
9. D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, “Composite medium with simultaneously negative permeability and permittivity,” Physical Review Letters, vol. 84, no. 18, pp. 4184–4187, 2000.
10. I. V. Lindell, S. A. Tretyakov, K. I. Nikoskinen, and S. Ilvonen, “BW media—Media with negative parameters, capable of supporting backward waves,” Microwave Opt. Tech. Letters, vol. 31, no. 2, pp. 129–133, Oct. 2001.
11. J. B. Pendry, “Negative refraction makes a perfect lens,” Phys. Rev. Letters, vol. 85, no.18, pp. 3966–3969, Oct. 2000.
12. Smith, D.R., Mock, J.J., Starr, A.F., Schurig, D.: Gradient index metamaterials. Phys. Rev. E, vol. 71, Issue. 3, pp. 036609 (2005)
13. J. B. Pendry, D. Schurig, and D. R. Smith, “Controlling electromagnetic fields,” Science, vol. 312, pp. 1780–1782, June 2006.
14. D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R.Smith, “Metamaterial electromagnetic cloak at microwave frequencies,” Science, vol. 314, pp. 977–980, November 2006.
15. Nader engheta, ’’Circuits with Light at Nanoscales: Optical Nanocircuits Inspired by Metamaterials,” Science, Vol. 317, no. 5845, pp. 1698-1702, 21 September 2007.
16. RichardW. ZIOLKOWSKI , “Metamaterial-Based Antennas: Research and Developments,” IEICE Trans. Electron., Vol.E89–C, NO.9, pp. 1267-1275, SEPTEMBER 2006
17. Tie Jun Cui, David Richard Smith, Ruopeng Liu Metamaterials: Theory, Design, and Applications , Publisher: Springer 2009
18. N. Engheta and R. W. Ziolkowski, Metamaterials: Physics and Engineering Explorations, Wiley-IEEE Press, 2006.
19. R. W. Ziolkowski, "Propagation in and Scattering from a Matched Metamaterial Having a Zero Index of Refraction," Phys. Rev. E, vol. 70, pp. 046608, October, 2004.
20. S. A. Tretyakov, S. I. Maslovski, and P. A. Belov, “An analytical model of metamaterials based on loaded wire dipoles,” IEEE Transactions on Antennas and Propagation, vol. 41, no. 10, pp. 2652–2658, 2003.
21. P. A. Belov, R. Marqués, S. I. Maslovski, I. S. Nefedov, M. Silveirinha, C. R. Simovski, and S. A. Tretyakov, “Strong spatial dispersion in wire media in the very large wavelength limit,” Physical Review B, vol. 67, p. 113103(1-4), 2003.
22. Philippe Gay-Balmaz and Olivier J. F. Martin, “Electromagnetic resonances in individual and coupled split-ring resonators,” Journal of Applied Physics, vol. 92, no. 5, pp. 2929–2936, 2002.

23. R. Marqués, F. Medina, and R. Rafii-El-Idrissi, “Role of bianisotropy in negative permeability and left-handed metamaterials,” Physical Review B, vol. 65, p. 144440(1-6), 2002.
24. N. Katsarakis, T. Koschny, M. Kafesaki, E. N. Economou, and C. M. Soukoulis, “Electric coupling to the magnetic resonance of split ring resonators,” Applied Physics Letters, vol. 84, no. 15, pp. 2943–2945, 2004.
25. J. D. Baena, R. Marqués, F. Medina, and J. Martel, “Artificial magnetic metamaterial design by using spiral resonators,” Physical Review B, vol. 69, p. 014402, 2004.
26. R. A. Shelby, D. R. Smith, S. C. Nemat-Nasser, and S. Schultz, “Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial,” Applied Physics Letters, vol. 78, no. 4, pp. 489–491,2001.
27. R. A. Shelby, D. R. Smith, and S. Schultz, “Experimental verification of a negative index of refraction,” Science, vol. 292, pp. 77–79, 2001.
28. C. R. Simovski and S. He, “Frequency range and explicit expressions for negative permittivity and permeability for an isotropic medium formed by a lattice of perfectly conducting omega particles,” Physics Letters A, vol. 311, pp. 254–263, 2003.
29. H. Chen, L. Ran, J. Huangfu, X. Zhang, K. Chen, T. M. Grzegorczyk, and J. A.Kong, “Left-handed materials composed of only S-shaped resonators,” Physical Review E, vol. 70, p. 057605, 2004.
30. J. Zhou, L. Zhang, G. Tuttle, T. Koschny, and C. M. Soukoulis, “Negative index materials using simple short wire pairs,” Physical Review B, vol. 73, p. 041101, January 2006.
31. M. Kafesaki, I. Tsiapa, N. Katsarakis, T. Koschny, C. M. Soukoulis, and E. N. Economou,“Left-handed metamaterials: The fishnet structure and its variations,” Physical Review B, vol. 75, p. 235114, June 2007.
32. O. G. Vendik and M. S. Gashinova, “Artificial double negative (DNG) media composed by two different dielectric sphere lattices embedded in a dielectric matrix,” in European Microwave Conference (EuMC), Amsterdam, 2004, pp. 1209–1212.
33. C. Caloz and T. Itoh, Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications. Wiley-Interscience and IEEE press, 2006.
34. 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 IEEE Antennas and Propagation Int. Symp. (AP-S) and USNC/URSI Meeting, vol. 2. San Antonio, TX: IEEE, June2002, pp. 412–415.
35. A. K. Iyer and G. V. Eleftheriades, “Negative refractive index metamaterials supporting 2-D waves,” in IEEE MTT-S Int. Microwave Symp. Dig., Seattle, WA, June 2002, pp. 1067–1070.
36. A. A. Oliner, “A periodic-structure negative-refractive-index medium without resonant elements,” in IEEE Antennas and Propagation Int. Symp. (AP-S) and USNC/URSI Meeting,San Antonio, TX, June 2002, p. 41.
37. C. Caloz and T. Itoh, “Transmission line approach of left-handed (LH) materials and microstrip implementation of an artificial LH transmission line,” IEEE Transactions on Antennas and Propagation, vol. 52, no. 5, pp. 1159–1166, 2004.
38. A. Sanada, C. Caloz, and T. Itoh, “Planar distributed structures with negative refractive index,” IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 4, pp. 1252–1263, 2004.
39. A. Grbic and G. V. Eleftheriades, “An isotropic three-dimensional negative-refractive index transmission-line metamaterial,” Journal of Applied Physics, vol. 98, p. 043106, August 2005.
40. M. Zedler and P. Russer, “Investigation on the dispersion relation of a 3D LC-based metamaterial with an omnidirectional left-handed frequency band,” in IEEE MTT-S Int. Microwave Symp. Dig., San Francisco , CA, June 2006, pp. 1477–1479.
41. M. Zedler, C. Caloz, and P. Russer, “A 3-D isotropic left-handed metamaterial based on the rotated transmission-line matrix (TLM) scheme,” IEEE Transactions on Microwave Theory and Techniques, vol. 55, no. 12, pp. 2930–2941, December 2007.
42. Smith, DR,” *Beating the diffraction limit*,” Physics World, vol. 17, no. 5, pp. 23-24, 2004.
43. Grbic, A., Eleftheriadesm, G.V.: Overcoming the diffraction limit with a planar left-handed transmission-line lens. Phys. Rev. Lett. 92, p. 117403, 2004.
44. Fang, N., et al, “ Sub-diffraction-limited optical imaging with a silver superlens,” Science, vol. 308, no. 5721, pp. 534-537, 2005.
45. Igor I., Smolyaninov, Yu-Ju Hung, Christopher C. Davis, "Magnifying Superlens in the Visible Frequency Range," Science, vol. 315, no. 5819, pp. 1699–1701, 2007.
46. B. D. F. Casse, W. T. lu, Y. J. Huang, E. Gultepe, L. Menon, S. Sridhar, "Super-resolution imaging using a three-dimensional metamaterials nanolens," Applied Physics Letters ,vol.96, no. 023114, pp. 1-3, 2010

47. R. Liu, C. Ji, J.J. Mock, J.Y.Chin,T.J.cui, D.R.smith, " Broadband ground-plane cloak," Science, vol. 323,no. 5912, pp. 366-369 2009.
48. Lucas H. Gabrielli, Jaime Cardenas, Carl B. Poitras, Michal Lipson , "Silicon nanostructure cloak operating at optical frequencies," Nature Photonics, vol. 3, pp. 461-463, 20 July 2009
49. Filiberto Bilotti, Simone Tricarico, Lucio Vegni, "Plasmonic metamaterial cloaking at optical frequencies,". arXiv:0807.4945 [physics.optics].(2008)
50. "Acoustic cloaking could hide objects from sonar" (Online). Information for Mechanical Science and Engineering (University of Illinois (Urbana-Champaign)). April 21, 2009. Retrieved 2011-02-01.
51. "Newly Developed Cloak Hides Underwater Objects From Sonar" (Online). U.S. News - Science (2011 U.S.News & World Report). January 7, 2011. Retrieved 2011-06-01.
52. Nelson, Bryn (January 19, 2011). "New metamaterial could render submarines invisible to sonar" (Online). Defense Update. Retrieved 2011-01-31.
53. R.W. Ziolkowski and A. Kipple, "Application of double negative metamaterials to increase the power radiated by electrically small antennas," IEEE Trans. Antennas Propag., vol.51, pp. 2626–2640, Oct. 2003.
54. R.W. Ziolkowski and A. Erentok, "Metamaterial-based efficient electrically small antennas," IEEE Trans. Antennas Propag., vol.54, no.7, pp. 2113–2130, July 2006.
55. Stefan Enach, G. Tayeb, P S Abouroux, N Guerin, P. Vincent, A Metamaterials for directive emission, phys. Rev. lett. Vol. 89, no. 21, pp. 213902-1—213902-4, 2002.
56. Das, Saswato R. (October 2009). "Metamaterials Arrive in Cellphones" (Online magazine article). Metamterial antennas. IEEE Spectrum. Retrieved 2011-03-09. "LG Chocolate BL40 is first cellphone to use a metamaterials antenna")
57. Fangming Zhu,Qingchun Lin, Jun Hu, "A Directive Patch Antenna with a Metamaterial Cover," Asia Pacific Microwave Conference Proceeding volume 3. Suzhou china 2005
58. Rui Wang, Bo Yuan, Gaofeng Wang, Fan Yi (2007). "Efficient Design of Directive Patch Antennas in Mobile Communications Using Metamaterials," International Journal of Infrared and Millimeter Waves, vol. 28, issue. 8, pp. 639-649, 2007.
59. Johnson, R. Colin (2009-07-23). "Metamaterial cloak could render buildings 'invisible' to earthquakes". EETimes.com. Retrieved 2009-09-09.
60. Barras, Colin (2009-06-26). "Invisibility cloak could hide buildings from quakes". New Scientist. Retrieved 2009-10-20.
61. llya V. Shadrivov, Polina V. kapitanova, Stanislavi. Maslovski and Yuris. Kivshar, "Metamaterials controlled with light," Phys. Rev. Lett., vol. 109, pp. 083902-1—083902-4 , (2012)
62. http://en.wikipedia.org/wiki/Tunable_metamaterials#cite_note-Lapine-structure-2
63. http://www.pratt.duke.edu/news/wireless-device-converts-lost-energy-electric-power.
64. Allen M.Hawkes, Alexander R.katko and Steven A.Cummer, "A microwave metamaterial with integrated power harvesting functionality," Applied Physics Letters, vol.103, pp. 163901, october2013.

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