ELectronics EXpress

REVIEW PAPER IEICE Electronics Express, Vol.9, No.2, 65–80

Mu-negative, double-negative, and composite right/left handed metamaterials based on dielectric resonators

Tetsuya Ueda[1a)] **and Tatsuo Itoh**[2]

[1] *Department of Electronics, Kyoto Institute of Technology*
Matsugasaki, Sakyo-ku, Kyoto 606–8585, Japan

[2] *Electrical Engineering Department, University of California at Los Angeles*
405 Hilgard Avenue, Los Angeles, CA 90095, USA

a) *ueda@kit.ac.jp*

Abstract: In this paper, dielectric-resonator-based metamaterials are reviewed. They are classified mainly into several schemes with explanations of their propagation mechanisms. In addition, recent progress on 1-D, 2-D, and 3-D composite right/left handed metamaterial structures based on one-dielectric-resonator scheme with magnetic dipoles embedded in ε-negative host medium are shown along with their applications.

Keywords: metamaterials, negative refractive index, left-handed materials, effective medium, Mie resonance, dielectric resonators

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] C. Caloz and T. Itoh, *Electromagnetic Metamaterials–Transmission Line Theory and Microwave Applications*, John Wiley & Sons, 2006.

[2] N. Engheta and R. W. Ziolkowski, *Metamaterials – Physics and Engineering Explorations*, New Jersey, IEEE Press, 2006.

[3] G. V. Eleftheriades and K. G. Balmain, *Negative Refraction Metamaterials: Fundamental Principles and Applications*, New Jersey, IEEE Press. Wiley, 2005.

[4] V. G. Veselago, "The electrodynamics of substances with simultaneously negative value of ε and μ," *Sov. Phys. Usp.*, vol. 10, no. 4, pp. 509–514, Jan. 1968.

[5] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.*, vol. 84, no. 18, pp. 4184–4187, May 2000.

[6] J. B. Pendry, "Negative Refraction makes a perfect lens," *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3966–3969, Oct. 2000.

[7] U. Leonhardt, "Optical Conformal Mapping," *Science*, vol. 312, pp. 1777–1780, June 2006.

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

[8] J. B. Pendry, D. Schurig, and D. R. Smith, "Controlling electromagnetic fields," *Science*, vol. 312, pp. 1780–1782, June 2006.
[9] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 11, pp. 2075–2084, Nov. 1999.
[10] A. Grbic and G. V. Eleftheriades, "An isotropic three-dimensional negative-refractive-index transmission line metamaterial," *J. Appl. Phys.*, vol. 98, pp. 043106-1–043106-5, Aug. 2005.
[11] P. Alitalo, S. Maslovski, and S. Tretyakov, "Three-dimensional isotropic perfect lens based on LC-loaded transmission lines," *J. Appl. Phys.*, vol. 99, pp. 064912-1–064912-8, March 2006.
[12] M. Zedler, C. Caloz, and P. Russer, "A 3-D isotropic left-handed metamaterial based on the rotated transmission-line matrix (TLM) scheme," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 12, pp. 2930–2941, Dec. 2007.
[13] Q. Zhao, J. Zhou, F. Zhang, and D. Lippens, "Mie resonance-based dielectric metamaterials," *Materials Today*, vol. 12, no. 12, pp. 60–69, Dec. 2009.
[14] I. Vendik, O. G. Vendik, and M. Odit, "Isotropic double-negative materials," *Metamaterials Handbook, Theory and Phenomena of Metamaterials*, Ch. 21, edited by F. Capolino, CRC Press, pp. 21.1–21.32, 2009.
[15] C. L. Holloway, E. Kuester, J. Baker-Javis, and P. Kabos, "A double negative (DNG) composite medium composed of magnetodielectric spherical particles embedded in a matrix," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2596–2601, Oct. 2003.
[16] O. G. Vendik and M. S. Gashinova, "Artificial double negative (DNG) media composed by two different dielectric sphere lattices embedded in a dielectric matrix," *Proc. Eur. Microw. Conf.*, pp. 1209–1212, Oct. 2004.
[17] L. Jylhä, I. Kolmakov, S. Maslovski, and S. Tretyakov, "Modeling of isotropic backward-wave materials composed of resonant spheres," *J. Appl. Phys.*, vol. 99, pp. 043102-1–043102-7, Feb. 2006.
[18] A. Ahmadi and H. Mosallaei, "Physical configuration and performance modeling of all-dielectric metamaterials," *Phys. Rev. B.*, 045104, pp. 1–11, Jan. 2008.
[19] S. Ghadarghadr and H. Mosallaei, "Dispersion diagram characteristics of periodic array of dielectric and magnetic materials based spheres," *IEEE Trans. Antennas Propag.*, vol. 57, no. 1, pp. 149–160, Jan. 2009.
[20] R. A. Shore and A. D. Yaghjian, "Traveling waves on three-dimensional periodic arrays of two different alternating magnetodielectric spheres," *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 3077–3091, Oct. 2009.
[21] E. A. Semouchkina, G. B. Semouchkin, M. Lanagan, and C. A. Randall, "FDTD study of resonance processes in metamaterials," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 4, pp. 1477–1486, April 2005.
[22] T. Ueda and T. Itoh, "Three-dimensional negative-refractive-index metamaterials composed of spherical dielectric resonators," *URSI National Radio Science 2006 Meeting Abstract*, p. 51, Jan. 2006.
[23] L. Peng, L. Ran, H. Chen, H. Zhang, J. A. Kong, and T. M. Grzegorczyk, "Experimental observation of left-handed behavior in an array of standard dielectric resonators," *Phys. Rev. Lett.*, 157403, pp. 1–4, April 2007.
[24] J. Kim and A. Gopinath, "Simulation of a metamaterial containing cubic high dielectric resonators," *Phys. Rev. B.*, 115126, pp. 1–6, Sept. 2007.
[25] K. Vynck, D. Felbacq, E. Centeno, A. I. Cabuz, D. Cassagne, and B. Guizal, "All-dielectric rod-type metamaterials at optical frequency,"

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

Phys. Rev. Lett., vol. 102, 133901, March 2009.
[26] B.-J. Seo, T. Ueda, T. Itoh, and H. Fetterman, "Isotropic left handed material at optical frequency with dielectric spheres embedded in negative permittivity medium," *Appl. Phys. Lett.*, vol. 88, 161122, April 2006.
[27] A.-G. Kussow, A. Akyurtlu, and N. Angkawisittpan, "Optically isotropic negative index of refraction metamaterial," *Phys. Stat. Sol.*, vol. 245, no. 5, pp. 992–997, Feb. 2008.
[28] L. Kahn and D. Lippens, "Mie resonance based left-handed metamaterial in the visible frequency range," *Phys. Rev. B*, vol. 83, 195125, May 2011.
[29] T. Ueda, A. Lai, and T. Itoh, "Negative refraction in a cut-off parallel-plate waveguide loaded with two-dimensional lattice of dielectric resonators," *Proc. Eur. Microw. Conf.*, pp. 435–438, Sept. 2006.
[30] T. Ueda, N. Michishita, A. Lai, and T. Itoh, "Leaky wave antenna based on left-handed transmission lines composed of a cut-off parallel plate waveguide loaded with dielectric resonators," *IEICE Trans. Electron.*, vol. E90-C, no. 9, pp. 1770–1775, Sept. 2007.
[31] T. Ueda, A. Lai, and T. Itoh, "Demonstration of negative refraction in a cut-off parallel-plate waveguide loaded with two-dimensional lattice of dielectric resonators," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 6, pp. 1280–1287, June 2007.
[32] T. Ueda, N. Michishita, M. Akiyama, and T. Itoh, "Dielectric-resonator-based composite right/left handed transmission lines and their application to leaky wave antenna," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 10, pp. 2259–2269, Oct. 2008.
[33] T. Ueda, N. Michishita, A. Lai, M. Akiyama, and T. Itoh, "2.5-D stacked composite right/left handed metamaterial structures using dielectric resonators and parallel mesh plates," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 335–338, June 2008.
[34] T. Ueda, S. Adachi, N. Michishita, M. Akiyama, and T. Itoh, "Multilayered volumetric composite right/left handed metamaterial structures composed of dielectric resonators and parallel mesh plates," *IEICE Trans. Electron.*, vol. E93-C, no. 7, pp. 1063–1071, July 2010.
[35] T. Ueda, N. Michishita, M. Akiyama, and T. Itoh, "Anisotropic 3-D composite right/left handed metamaterial structures using dielectric resonators and conductive mesh plates," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 7, pp. 1766–1773, July 2010.
[36] Y. Sato, T. Ueda, Y. Kado, and T. Itoh, "Design of isotropic 3-D multilayered CRLH metamaterial structures using conductive mesh plates and dielectric resonators," *Proc. 2011 Asia-Pacific Microw. Conf.*, pp. 526–529, Dec. 2011.
[37] M. Notomi, "Theory of light propagation in strongly modulated photonic crystal: refractionlike behavior in the vicinity of the photonic band gap," *Phys. Rev. B*, vol. 62, no. 16, pp. 10696–10705, Oct. 2000.
[38] C. Luo, S. G. Johnson, and J. D. Joannopoulos, "All-angle negative refraction in a three-dimensionally periodic photonic crystal," *Appl. Phys. Lett.*, vol. 81, no. 13, pp. 2352–2354, Sept. 2002.
[39] E. Cubukcu, K. Aydin, E. Ozbay, S. Foteinopoulou, and C. M. Soukulis, "Negative refraction by photonic crystals," *Nature*, vol. 423, pp. 604–605, June 2003.
[40] E. Cubukcu, K. Aydin, E. Ozbay, S. Foteinopolou, and C. M. Soukoulis, "Subwavelength Resolution in a Two-Dimensional Photonic-Crystal-Based Superlens," *Phys. Phys. Lett.*, vol. 91, no. 20, 207401, pp. 1–4, Nov. 2003.
[41] J. Valentine, J. Li, T. Zentgraf, G. Bartal, and X. Zhang, "An optical

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

cloak made of dielectrics," *Nature Materials*, vol. 8, pp. 568–571, April 2009.

[42] J. H. Lee, J. Blair, V. A. Tamma, Q. Wu, S. J. Rhee, C. J. Summers, and W. Park, "Direct visualization of optical frequency invisibility cloak based on silicon nanorod array," *Opt. Express*, vol. 17, no. 15, pp. 12922–12928, July 2009.

[43] T. Ergin, N. Stenger, P. Brenner, J. B. Pendry, and M. Wegener, "Three-dimensional invisibility cloak at optical wavelengths," *Science*, vol. 328, pp. 337–339, April 2010.

[44] D. P. Gaillot, C. Croënne, and D. Lippens, "An all-dielectric route for terahertz cloaking," *Optics Express*, vol. 16, no. 6, pp. 3986–3992, March 2008.

[45] E. Semouchkina, D. H. Werner, G. B. Semouchkin, and C. Pantano, "An infrared invisibility cloak composed of glass," *Appl. Phys. Lett.*, vol. 96, no. 13, 233503, June 2010.

[46] 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, Nov. 2006.

[47] L. Lewin, "The electrical constants of a material loaded with spherical particles," *Proc. Inst. Elec. Eng.*, vol. 94, Part III, pp. 65–68, 1947.

[48] S. O'Brien and J. B. Pendry, "Photonic band-gap effects and magnetic activity in dielectric composites," *J. Phys. Condens. Matter*, vol. 14, pp. 4035–4044, 2002.

[49] J. A. Schuller, R. Zia, T. Taubner, and M. L. Brongersma, "Dielectric metamaterials based on electric and magnetic resonances of silicon carbide particles," *Phys. Rev. Lett.*, 107401, Sept. 2007.

[50] B.-I. Popa and S. A. Cummer, "Compact dielectric particles as a building block for low-loss magnetic metamaterials," *Phys. Rev. Lett.*, 207401, May 2008.

[51] Q. Zhao, L. Kang, B. Du, H. Zhao, Q. Xie, X. Huang, B. Li, J. Zhou, L. Li, "Experimental demonstration of isotropic negative permeability in a three-dimensional dielectric composite," *Phys. Rev. Lett.*, vol. 101, 027402, July 2008.

[52] K. Shibuya, K. Takano, N. Matsumoto, K. Izumi, H. Miyazaki, Y. Jimba, and M. Hangyo, "Terahertz metamaterials composed of TiO_2 cube arrays" *2nd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics*, pp. 777–779, Sept. 2008.

[53] T. Giannakopoulou, D. Niarchos, and C. Trapalis, "Experimental investigation of electric and magnetic responses in composites with dielectric resonator inclusions at microwave frequencies," *Appl. Phys. Lett.*, vol. 94, 242506, June 2009.

[54] H. Nemec, P. Kuzel, F. Kadlec, C. Kadlec, R. Yahiaoui, and P. Mounaix, "Tunable terahertz metamaterials with negative permeability," *Phys. Rev. B*, vol. 79, 241108(R), June 2009.

[55] R. Marques, J. Martel, F. Mesa, and F. Medina, "Left handed media simulation and transmission of EM waves in sub-wavelength SRR-loaded metallic waveguides," *Phys. Rev. Lett.*, vol. 89, 183901, Oct. 2002.

[56] T. Yoshida, T. Ueda, M. Akiyama, and T. Itoh, "Radiation characteristics of zeroth- order resonators composed of 2-D dielectric-based composite right/left handed metamaterial structures," *Proc. 39th Eur. Microw. Conf.*, pp. 205–208, Sept. 2009.

[57] A. Sanada, C. Caloz, and T. Itoh, "Zeroth-order resonance in composite right/left handed transmission line resonators," *Proc. Asia-Pacific Microw. Conf.*, pp. 1588–1592, 2003.

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

ELectronics EXpress

[58] A. Sanada, M. Kimura, I. Awai, C. Caloz, and T. Itoh, "A planar zeroth-order resonator antenna using a left-handed transmission line," *Proc. 34th Eur. Microw. Conf.*, pp. 1341–1344, 2004.
[59] K. Seki, T. Ueda, M. Akiyama, and T. Itoh, "Open-ended zeroth-order resonators using dielectric metamaterials," *Proc. 40th Eur. Microw. Conf.*, pp. 445–448, Sept. 2010.

1 Introduction

Metamaterials are artificial electromagnetic/light wave-guiding structures that are composed of elements, referred to as unit cells, much smaller than a wavelength of an incident wave [1, 2, 3]. The macroscopic behavior of artificial multiple electric and magnetic dipoles in the composite structures, which are controlled by designing shapes and alignments of the unit cells and are excited in response to the incident waves, governs the constitution relation of the "effective" medium, in analogy to electric and magnetic polarizations of molecules/atoms in nature. The metamaterials can bring fascinating electromagnetic phenomena and technologies, such as negative refraction [4, 5], superlenses with subwavelength resolution [6], cloaking techniques that make objects invisible [7, 8], transformation optics, state-of-the-art microwave/millimeter-wave circuits and antennas [1, 2, 3], and so forth. Negative-refractive-index metamaterials or left-handed metamaterials have negative effective permittivity and negative permeability simultaneously, and support backward wave propagation with wavenumber vectors anti-parallel to the transmitted power direction [4, 5]. Most of the unit cells designed to achieve negative permeability in the early work contained resonant circuits with Lorentz-type dispersion, such as split ring resonator (SRR) [9]. The resonant-type metamaterials are readily extended to the 2-D and 3-D structures without direct connections between individual elements. But they suffer from the conductor loss near the resonant frequencies. Transmission-line-type metamaterials without Lorentz-type dispersion in both permittivity and permeability were proposed and developed due to the relatively low loss and easy applications to microwave circuits [1, 2, 3]. But the extension of such transmission-line-based structures into 3-D left-handed metamaterials would have the difficulties in fabrication of the LC networks with considerably complex configuration [10, 11, 12].

For the purpose of conductor loss reduction and simplification of configurations for fabrication, left-handed metamaterials using nonmetallic dielectric resonators were proposed in various configurations [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36]. The most typical one is a two-dielectric-resonator scheme [15, 16, 17, 18, 19, 20] with two different electric and magnetic dipole moment-like resonances. Since the operational bandwidth is very narrow due to high quality factors of the resonators, this scheme is very dispersive and would have the difficulty in achieving double negative condition for fabrication. The second type is a one-

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

IEICE Electronics Express, Vol.9, No.2, 65–80

dielectric-resonator scheme using their mutual coupling [21, 22, 23, 24, 25]. This scheme has a relatively wide bandwidth due to low-Q of resonators to maintain the mutual coupling, but the lattice type of resonators is important and determines the left-handedness. With a low dielectric-constant material in the dielectric resonators, the resonator's size becomes comparable to the half wavelength, and the mechanisms of the left-handed transmission would be analogous to negative refraction in photonic crystals [37, 38, 39, 40]. The above-mentioned two different schemes are composed of all-dielectric metamaterials. However, both schemes show a positive-refractive-index at off-resonant frequencies, and this condition allows propagation of right-handed modes at low frequencies.

In recent years, another configuration of one-dielectric-resonator scheme has been proposed by using a hybrid combination with a metal-based ε-negative host medium. In optical region, plasmonic materials with plasma frequency higher than the operational frequency can be regarded as ε-negative media [18, 26, 27, 28], and so can be TE cut-off waveguide structures in the microwave/millimeter waves as well as in the terahertz region [29, 30, 31, 32, 33, 34, 35, 36]. In this scheme, negative permeability is achieved by magnetic dipole moment-like resonance of dielectric resonators, and negative permittivity is obtained by non-resonant metal-based structures. The most outstanding advantage of this hybrid scheme is to be able to avoid undesired mode excitation in the host medium below the plasma (or TE cut-off) frequency, and only μ-negative mechanism due to the magnetic dipoles can excite a dominant left-handed mode. Some other configurations with plasmonic particles do not utilize such cut-off characteristics [28].

In recent work on transformation optics, spatial mapping of effective permittivity has been made by distributing non-resonant dielectric elements into a host medium for realization of cloaking with almost dispersionless characteristics [41, 42, 43]. It is noted that such a manner of manipulation of dielectric constant is conventional in optics, except for the mathematical concept of the transformation. Some other composite structures for cloaking were designed by distributing resonant-type dielectrics into the host medium in order to manipulate effective permeability [44, 45]. The latter approach is very dispersive but is considered more intrinsic to metamaterials, in the same manner as SRR [46].

In this paper, dielectric-resonator-based metamaterials are reviewed. They are classified mainly into three schemes, and the transmission mechanisms are explained by using equivalent circuit models. In addition, recent progress on one-dielectric-resonator scheme in hybrid combination with metal-based ε-negative host medium and their applications will be shown.

2 Magnetic dipole moment-like resonance in dielectric resonators and μ-negative metamaterials

In this section, we consider a composite structure that is composed of a 3-D array of identical dielectric spheres with high dielectric constant. In the

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

configuration, each dielectric sphere behaves like a magnetic dipole moment under the resonance in a specific frequency region, in the same manner as SRR, and macroscopic behavior of the multiple dipoles can significantly affect the effective permeability. In another frequency region, electric dipole moment-like resonance occurs in the sphere and affects the effective permittivity. When a plane wave is externally incident to the composite structure at the frequency near the resonances, the wave excites and is strongly coupled to the resonant modes. When the mutual coupling between neighboring resonators is weak, the effective permittivity and permeability are approximately formulated by Lewin [13, 14, 15, 16, 17, 18, 19, 20, 26, 27, 47] as,

$$\begin{aligned} \varepsilon_{eff} &= \varepsilon_{BG}\left[1+\frac{3v_f}{(F(\theta)+2b_e)/(F(\theta)-b_e)-v_f}\right], \\ \mu_{eff} &= \mu_{BG}\left[1+\frac{3v_f}{(F(\theta)+2b_m)/(F(\theta)-b_m)-v_f}\right]. \\ b_e &= \varepsilon_{BG}/\varepsilon_{DR}, b_m = \mu_{BG}/\mu_{DR}, F(\theta) \\ &= 2(\sin\theta-\theta\cos\theta)/[(\theta^2-1)\sin\theta+\theta\cos\theta], \\ \theta &= k_0 a\sqrt{\varepsilon_{DR}\mu_{DR}}/2 \end{aligned} \quad (1)$$

where a and ν_f represent the radius and volume fraction of dielectric spheres in the structure, respectively. The subscripts of variables in (1), DR and BG, denote the physical quantities in the dielectric resonator and host medium, respectively. Effective permittivity and permeability evaluated from (1) are plotted for the lossless cases in Fig. 1. In Fig. 1 (a), the effective permeability shows Lorentz-type dispersion around the fundamental TE resonance with the normalized frequency a/λ of $0.09 - 0.10$. In the frequency region near and above the resonance, effective permeability takes negative values, and the bandwidth of negative region is increased with density of the resonators. The permittivity in Fig. 1 (b) does not show such singularities at the same frequency. Thus, the composite structure with the array of identical dielectric spheres can be a single μ-negative metamateial. The second higher-order resonant mode of dielectric sphere is a fundamental TM mode and shows an electric dipole moment-like resonance. From Fig. 1 (b), the resonance is

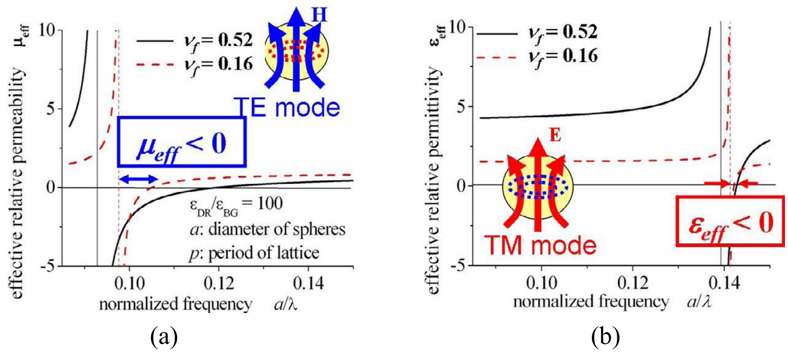

Fig. 1. Effective permeability and permittivity as a function of frequency and the density. (a) Effective permeability. (b) Effective permittivity.

© IEICE 2012
DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

IEICE Electronics Express, Vol.9, No.2, 65–80

found at a/λ of 0.14 and ε-negative characteristics are observed on the upper side of the resonant frequency.

The transmission characteristics in the array of spheres are expressed with the help of equivalent circuit models, as shown in Figs. 2 and 3. When the magnetic dipole moment-like resonance is excited by the magnetic field of the propagating wave, the wave propagation is expressed by the mutual magnetic coupling between a LC loop and a series inductance in the transmission-line ladder network, as shown in Fig. 2 (b). The effective series inductance L_{eff} and shunt capacitance C_{eff}, in the network, which correspond to effective permeability and permittivity, are given in terms of circuit parameters by

$$L_{eff} = L_0(1-k_m^2)\frac{\omega^2-\omega_{sM}^2}{\omega^2-\omega_{rM}^2}, C_{eff} = C_0, \omega_{rM}^2 = \frac{1}{L_{rM}C_{rM}},$$
$$\omega_{sM}^2 = \frac{\omega_{rM}^2}{1-k_m^2} > \omega_{rM}^2, k_m = \frac{L_m}{\sqrt{L_0 L_{rM}}}. \quad (2)$$

The frequency dependence of effective series inductance in (2) is illustrated in Fig. 2 (c), and represents the Lorentz-type dispersion, which corresponds to Fig. 1 (a). The frequency region between ω_{rM} and ω_{sM} in (2) shows negative permeability. For the electric dipole moment-like resonance, the transmission is expressed by an electrical coupling of another LC loop to the shunt capacitance, as shown in Fig. 3 (b). In this case, the effective permittivity has Lorentz-type dispersion, and takes negative values above the resonant frequency, as shown in Fig. 3 (c).

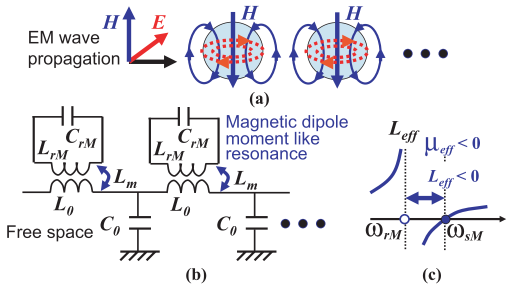

Fig. 2. Magnetic dipole moment-like fundamental TE resonant mode of dielectric spheres. (b) Equivalent circuit model. (c) Effective series inductance.

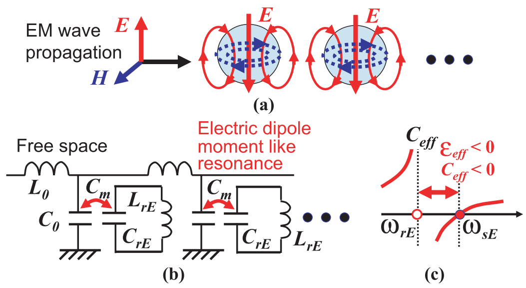

Fig. 3. Electric dipole moment-like fundamental TM resonant mode of dielectric spheres. (b) Equivalent circuit model. (c) Effective shunt capacitance.

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

IEICE Electronics Express, Vol.9, No.2, 65–80

In the following discussion, we will focus on the magnetic dipole moment-like resonance of dielectrics, specifically the cylindrical type. The selection of shape of dielectric resonators, e.g. spheres, cylinders, rods, cubes, or others is not important to achieve the dipole-like resonances, but restricts polarization directions and frequency dependences [47, 48, 49, 50, 51, 52, 53, 54].

3 Classification of dielectric-resonator-based metamaterials

In this section, we will classify dielectric-resonator-based left-handed metamaterials, from a propagation mechanism point of view. One of the most typical configurations is a two-dielectric-resonator scheme [15, 16, 17, 18, 19, 20], in which there are two different types of resonators; the one is under the magnetic dipole moment-like resonance in order to control the effective permeability, and the other is under the electric dipole moment-like resonance so as to steer the effective permittivity, as illustrated in Fig. 4. Therefore, the double negative condition is realized by appropriately adjusting the resonant frequencies and densities of these resonators. The transmission in the scheme is expressed by a circuit model with a combination of Figs. 2 (b) and 3 (b), that is, a LC loop for magnetic dipoles is magnetically coupled to the series inductive element in the ladder network, whereas another LC loop for electric dipoles is electrically coupled to the shunt capacitive elements.

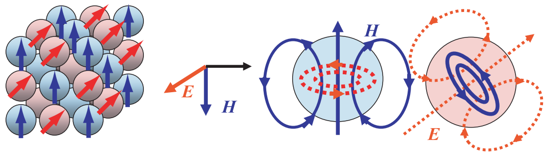

Fig. 4. Two-dielectric-resonator scheme for double-negative metamaterials.

The second typical configuration is a one-dielectric-resonator scheme using magnetic dipole-like resonance and their mutual coupling [21, 22, 23, 24, 25]. The left-handed transmission characteristics are explained by a circuit model with a chain of magnetically coupled LC loops, as shown in Fig. 5. The converted equivalent circuit provides a series resonant circuit in series branch and a shunt inductive element, resulting in double negative condition.

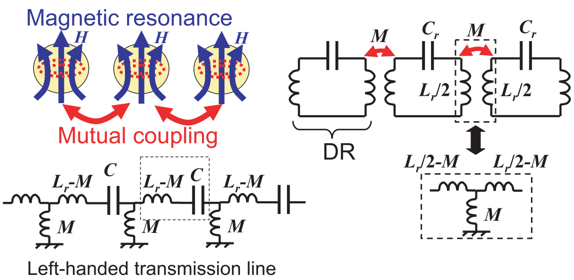

Fig. 5. One-dielectric-resonator scheme using mutual magnetic coupling for double-negative metamaterials.

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

The 2-D structures based on the scheme are readily constructed, such as with dielectric rods.

Another configuration of one-dielectric-resonator scheme is a hybrid combination with magnetic dipole moment-like resonators embedded in the metal-based ε-negative host medium, as shown in Fig. 6. Such an ε-negative host medium is realized by the use of plasmonic materials in optical region, as shown in Fig. 6 (a) [18, 26, 27, 28]. In the microwave, millimeter-wave and up to terahertz frequency region, TE cut-off metallic waveguides [55] provide negative effective permittivity below the cut-off frequency [29, 30, 31, 32, 33, 34, 35, 36], in which polarization of the incident wave is parallel to the two metallic plates with the distance smaller than the half wavelength, as illustrated in Fig. 6 (b). The circuit model for the unit cell is shown in Fig. 6 (c). The TE cut-off waveguide is described by the ladder network with a series inductance and shunt parallel resonant circuit. The shunt parallel resonant frequency corresponds to the cut-off frequency, and indicates zero effective permittivity. The interaction of the TE-cut-off waveguide with magnetic dipoles results in Lorentz-type dispersion in effective permeability. The permittivity does not show such singularities. When the series resonant frequency in series branch is the same as the shunt parallel resonant frequency in the scheme, a band gap between left and right handed modes disappears, referred to as balanced composite right/left handed (CRLH) metamaterials. Indeed, the configurations including metals in part may enhance conductor loss. However, the loss will not be so significant unless the conductors are employed in Lorentz-type resonators. It should be emphasized that in this scheme double negative condition is realized independently of Q factors of

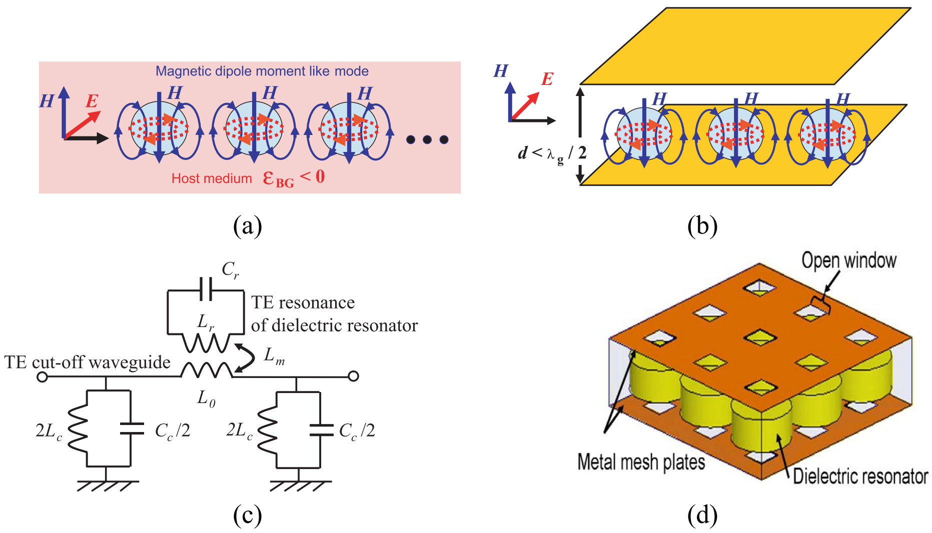

Fig. 6. One-dielectric-resonator scheme in combination with ε-negative structures. (a) Dielectric resonators embedded in plasma medium. (b) Dielectric resonators inserted in TE-cut-off waveguides. (c) Equivalent circuit model. (d) 2-DCRLH structure.

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

IEICE Electronics Express, Vol.9, No.2, 65–80

resonators, except for lossy materials, and is easily extended to 2-D structures, as shown in Fig. 6 (d).

4 One dielectric-resonator scheme in hybrid combination with metal-based ε-negative host medium and its applications

In this section, we will review recent progress on CRLH metamaterials based on one-dielectric-resonator scheme with magnetic dipoles embedded in TE cut-off waveguide structures in the microwave region. The 1-D, 2-D and 3-D CRLH metamaterial structures and their applications will be shown.

4.1 One-dimensional CRLH structures and leaky wave antenna application

As mentioned in the previous section, balanced CRLH transmission lines can be designed in the present scheme and implemented in the same manner as conventional printed circuit-type. One example of the applications is to frequency-scanned backfire-to-endfire leaky wave antennas [32]. Fundamental $TE_{01\delta}$ resonant mode in dielectric disc with the magnetic dipole moment-like field profiles is employed to achieve negative permeability. The geometry of the designed leaky wave antenna operating with 30 cells at X band is shown in Fig. 7. The beam angle is taken from the broadside to the forward direction, and the simulated radiation angles at 11.0 GHz, 11.5 GHz, and 12.0 GHz are −46 deg., 4 deg., and 52 deg., respectively. The corresponding antenna gains are 9.6 dBi, 10.5 dBi, and 11.2 dBi, respectively. This leaky wave antenna provides continuous backfire-to-endfire radiation, and that the beam steering angle of 100 degrees has been achieved with steady gain of about 10 dBi.

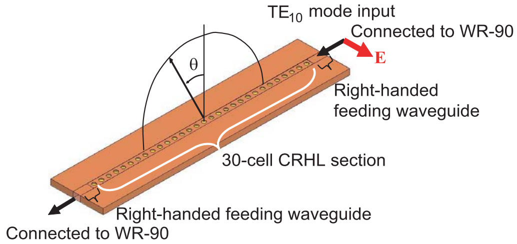

Fig. 7. Geometry of the 1-D CRLH leaky wave antenna (After [32] © 2008 IEEE).

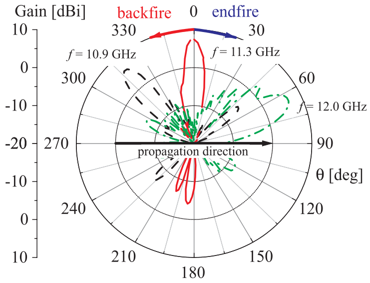

Fig. 8. Beam scanning characteristics. (After [32] © 2008 IEEE).

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

Measured radiation patterns shown in Fig. 8 verify the numerical simulation results.

4.2 Two-dimensional CRLH structures and zeroth-order resonator antennas

The concept of dielectric-resonator-based CRLH transmission lines is extended into 2-D structures [29, 31], and can be applied to zeroth order resonators [56]. It is well-known that resonant frequencies of zeroth order resonators do not depend on the whole size of the resonators but on the unit cell. In addition, they provide uniform field distribution in the phase and magnitude along the structure [57]. To date, zeroth order resonance was investigated for miniaturization of antennas [58], gain enhancement of the antennas, and microwave power dividers. In Fig. 9, a 2-D large-scale zeroth-order resonator antenna using dielectric-resonator-based CRLH metamateri-

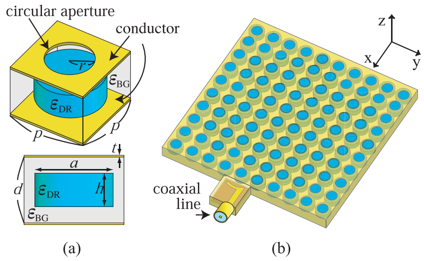

Fig. 9. Geometry of the 2-D zeroth order resonator (After [56] © 2008 IEEE).

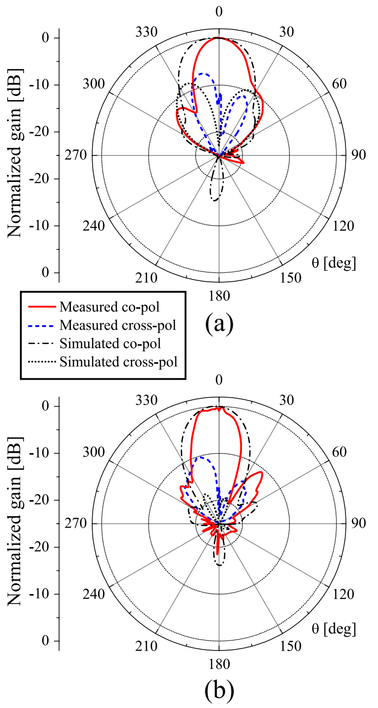

Fig. 10. Measured radiation pattern for 9 × 9 cells (After [56] © IEEE 2008). (a) In the H-plane. (b) In the E-plane.

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

IEICE Electronics Express, Vol.9, No.2, 65–80

als is illustrated [56]. It is composed of a 2-D array of disc-type dielectric resonators inserted in the parallel-plate waveguide with open windows on the top wall as an aperture to the air. The side walls are covered with conductor. The conducting side walls correspond to short ended terminals of zeroth-order resonators. In this case, series resonance in series branch is dominant and the fields are well-confined in dielectric resonators, as predicted from Fig. 6 (c). The balanced CRLH metamaterial was designed and employed in the resonator antenna. In Fig. 10, the measured radiation patterns for 9×9 cells are shown along with the numerical results. The measured patterns in both E- and H-planes are in good agreement with the simulation results. In addition, open-ended zeroth-order resonator antenna is also demonstrated for the 1-D structure [59]. Parallel resonance in the shunt branch is dominant for open-ended case, and current flow on mesh plates near apertures is significant. It is confirmed that the gain for open-ended cases is much enhanced compared to the short ended cases.

4.3 Volumetric 2-D and 3-D CRLH structures

In this section, multilayered volumetric 2-D and 3-D CRLH metamaterial structures are reviewed. Geometry of the multilayered volumetric 2-D CRLH metamaterial structure is shown in Fig. 11 [33, 34]. It is composed of a conducting mesh plate and a dielectric layer including dielectric resonators. The volumetric CRLH metamaterials support almost isotropic 2-D CRLH transmission near Γ point in the dispersion diagram for the in-plane propagation. In the configuration, the aperture size in conductive mesh plates is optimally selected so that both balanced CRLH transmission and impedance matching to free space are achieved. However, this volumetric structure did not support CRLH transmission in the normal direction. The present stacked structure has essentially uniaxial anisotropic characteristics, as found from Fig. 11. In order to achieve less anisotropic 3-D CRLH transmission characteristics for the multilayered structures, we attempt to make the anisotropy as small as possible for propagation directions parallel and normal to the mesh plates at the expense of impedance matching to free space [35]. It is noted that polarizations of the electric fields are limited to be in mesh plates.

For wave propagation normal to the stacked layers, $HE_{11\delta}$ resonant mode of dielectric disc is employed to obtain positive and negative effective perme-

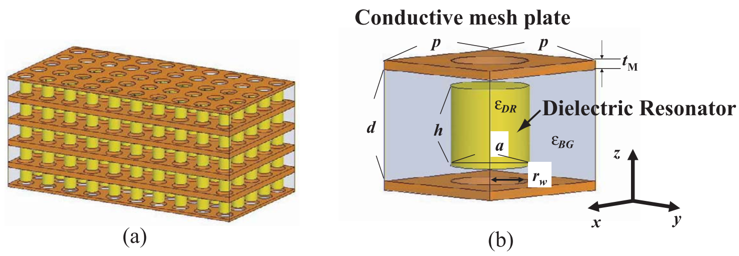

Fig. 11. Geometry of the 3-D multilayered CRLH metamaterial structures. (a) Perspective view. (b) Unit cell. (After [35] © 2010 IEEE)

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

IEICE Electronics Express, Vol.9, No.2, 65–80

ability. In order for $TE_{01\delta}$ and $HE_{11\delta}$ resonant modes of dielectric disc to be degenerate at the same operational frequency, the height and the diameter of the disc are set to be about the same. When designing the effective permittivity of the structure, the unit cell can be separated into two sections; a dielectric layer section including dielectric resonators, and conducting mesh plate sections. The effective permittivity of the former section is always positive, whereas the aperture hole below the cut off region has negative permittivity. Therefore, the effective permittivity of the whole structure can provide positive and negative permittivity. By adjusting configuration parameters in order for both frequencies at zero permittivity and zero permeability to coin-

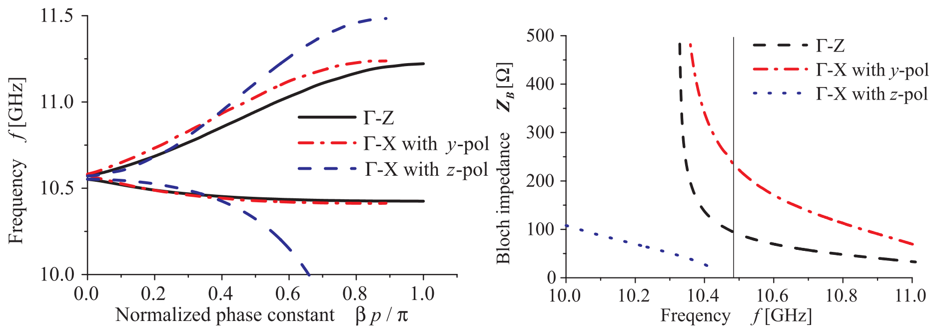

Fig. 12. Dispersion diagram and wave impedance (After [35] © 2010 IEEE).

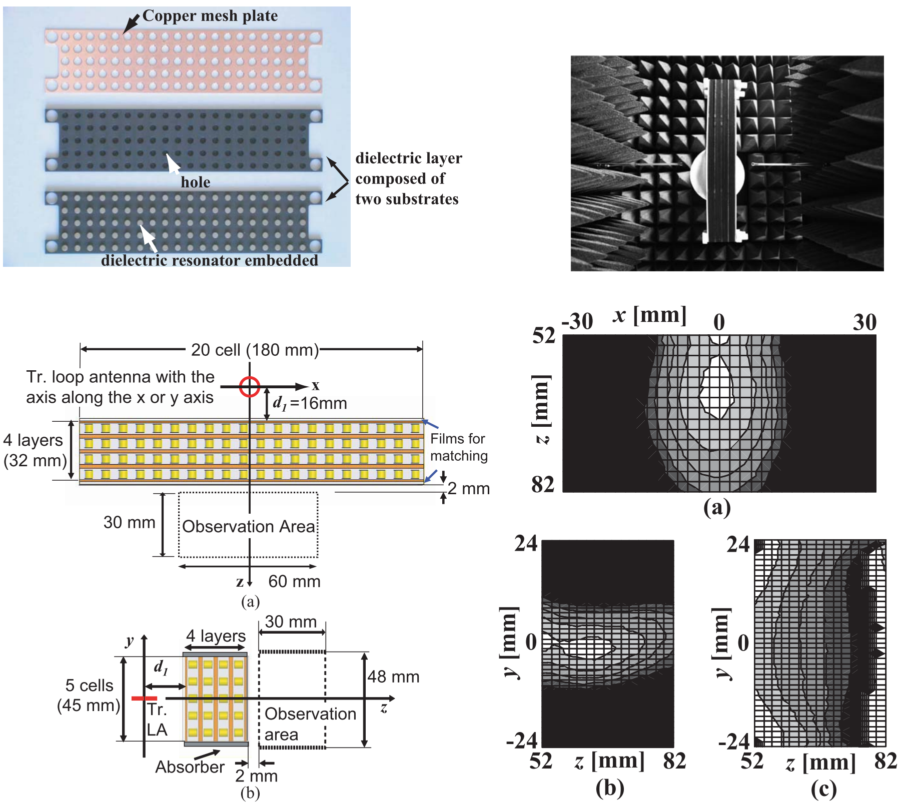

Fig. 13. Negative refractive index flat lens and measurement system of the near field distribution (After [35] © 2010 IEEE).

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

cide with each other, balanced CRLH structures for the propagation normal to the stacked layers can be designed.

In Fig, 12, dispersion diagrams and the wave impedances of the designed 3-D CRLH metamaterial structure are shown. It is found from Fig. 12 that balanced CRLH structure is designed not only in the parallel propagation directions, but also in the normal direction, and almost isotropic characteristics are achieved around Γ point in the dispersion characteristics. However, the structure is still significantly anisotropic from a wave impedance point of view. It is found from our recent research achievement [36] that almost isotropic characteristics not only in the dispersion diagram but also in the wave impedance are achieved by using higher dielectric constant material and making the unit cells much smaller. Negative-refractive-index flat focusing lens is demonstrated by using the 3-D multilayered CRLH metamaterials. The prototype lens, measurement system, and measured field patterns are shown in Fig. 13. The magnetic field patterns were measured with a small loop antenna, and the beam focusing was verified through the flat lens from the field patterns.

5 Conclusion

In this paper, dielectric-resonator-based metamaterials were reviewed, and were classified mainly into three schemes with explanations of their transmission mechanisms. In addition, recent progress on 1-D, 2-D, and 3-D CRLH structures based on one-dielectric-resonator scheme in hybrid combination with metal-based ε-negative host medium were shown along with their applications.

Acknowledgments

This work was supported in part by KAKENHI (22109002), from The Ministry of Education, Culture, Sports, Science and Technology, Japan.

Tetsuya Ueda
received the B.E., M.E., and Ph.D. degrees in communication engineering from Osaka University, Osaka, Japan, in 1992, 1994, and 1997, respectively. Since 1997, he has been with the Department of Electronics, Kyoto Institute of Technology, Kyoto, Japan, where he is currently an assistant professor. From 2005 to 2006, he was a Visiting Scholar with the Department of Electrical Engineering, University of California at Los Angeles. His current research interests include metamaterials and their applications. Dr. Ueda is a senior member of the IEEE. He was the recipient of the 1999 IEICE Young Engineer Award and the 2008 IEEE Microwave Theory and Techniques Society (MTT-S) Japan Chapter Young Engineer Award.

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012

IEICE Electronics Express, Vol.9, No.2, 65–80

Tatsuo Itoh
received the Ph.D. Degree in Electrical Engineering from the University of Illinois, Urbana in 1969. After working for University of Illinois, SRI and University of Kentucky, he joined the faculty at The University of Texas at Austin in 1978, where he became a Professor of Electrical Engineering in 1981. In September 1983, he was selected to hold the Hayden Head Centennial Professorship of Engineering at The University of Texas. In January 1991, he joined the University of California, Los Angeles as Professor of Electrical Engineering and holder of the TRW Endowed Chair in Microwave and Millimeter Wave Electronics (currently Northrop Grumman Endowed Chair). He received a number of awards including IEEE Third Millennium Medal in 2000, and IEEE MTT Distinguished Educator Award in 2000. He was elected to a member of National Academy of Engineering in 2003. In 2011, he received Microwave Career Award from IEEE MTT Society. Dr. Itoh is a Fellow of the IEEE, a member of the Institute of Electronics and Communication Engineers of Japan, and Commissions B and D of USNC/URSI. He served as the Editor of IEEE Transactions on Microwave Theory and Techniques for 1983-1985. He was President of the Microwave Theory and Techniques Society in 1990. He was the Editor-in-Chief of IEEE Microwave and Guided Wave Letters from 1991 through 1994. He was elected as an Honorary Life Member of MTT Society in 1994. He was the Chairman of Commission D of International URSI for 1993-1996, the Chairman of Commission D of International URSI for 1993-1996. He serves on advisory boards and committees of a number of organizations. He served as Distinguished Microwave Lecturer on Microwave Applications of Metamaterial Structures of IEEE MTT-S for 2004 – 2006. He has 400 journal publications, 820 refereed conference presentations and has written 48 books/book chapters in the area of microwaves, millimeter-waves, antennas and numerical electromagnetics. He generated 73 Ph.D. students.

DOI: 10.1587/elex.9.65
Received December 28, 2011
Accepted December 28, 2011
Published January 25, 2012