Review

Metamaterials and Automotive Applications

Kazuo Sato

Abstract

Metamaterials are a new class of ordered composites that exhibit unusual electromagnetic properties that are not readily observed in nature. These artificial materials with their simultaneously negative permittivity and permeability properties have attracted widespread interest in recent years. They are constructed from an array of metallic material in dielectric and magnetic substrates and exhibit unusual electromagnetic properties. Recent research into metamaterials has not only demonstrated interesting physical phenomena but has also lead to the development of design procedures and the realization of promising new types of microwave, millimeter-wave and optical components and devices. New-type metamaterials would open up a new field of automotive electronics applications, such as beam-scanned antenna systems for radar and mobile communications, novel magnetic materials for electric motors and the high-performance absorbing and shielding materials need for electromagnetic compatibility, and optical devices such as LED headlights and night vision systems using infrared cameras. In this review, we present a survey of metamaterials and present an overview of our recent R&D activities related to metamaterial design and their application to mobile antennas.

Keywords Metamaterials, Microwave, Millimeter-wave, Optics, Antennas, Topology optimization

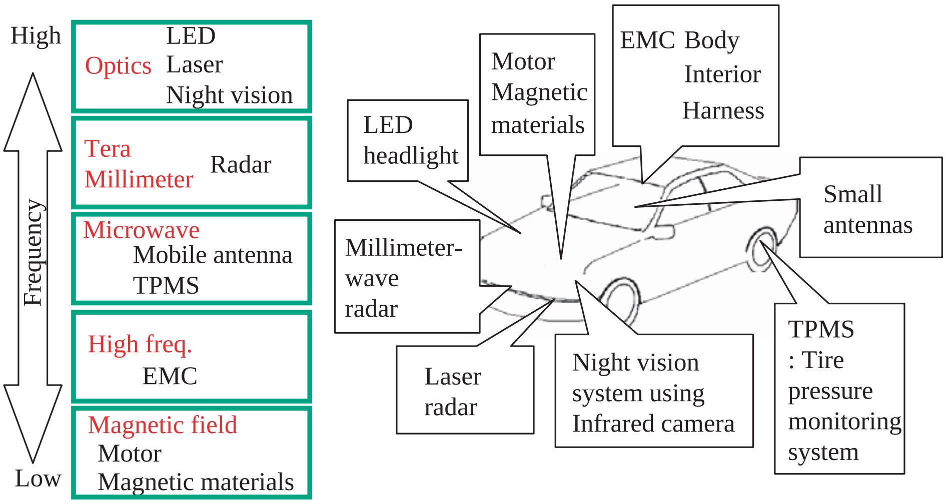
1. Introduction

Metamaterials are a new class of ordered composites that exhibit unusual electromagnetic properties that are not readily observed in nature. There is currently considerable interest in the development of metamaterials, with particular emphasis on double-negative (DNG) materials, i.e., artificial materials with simultaneously negative permittivity and permeability. DNG materials are referred to by several names, including left-handed (LH) materials, and negative index of refraction (NIR) materials. Recent research into metamaterials has not only demonstrated interesting physical phenomena but has also lead to the development of design procedures and the realization of new types of electromagnetic components and devices. Significant research effort has been expended in the development of microwave and millimeter-wave applications for metamaterials, such as couplers, resonators, small antennas, and beam-scanned leaky-wave antennas. In addition, there is nowadays considerable interest in the development of optics applications such as a negative index planar lens, called the "superlens".

We believe that these new types of electromagnetic components and devices will find many uses in future automotive electronics applications, as shown in **Fig. 1**. Low-cost, compact and beam-scanning antennas will be required for future radar systems and mobile communications systems. For electric vehicles, there will be a huge demand for novel high-performance magnetic materials for use in electric motors and the high-performance absorbing and shielding materials that are needed to ensure electromagnetic compatibility. Furthermore, photonics metamaterials should greatly improve the performance of automotive optical devices such as light-emitting diode (LED) headlights, laser-based sensing systems, and night-vision systems that use infrared cameras.

This special issue, entitled "Metamaterials and Automotive Applications", presents recent research in the area of metamaterials, undertaken at Toyota Central R&D Labs. This includes numerical and experimental contributions to the design of metamaterials and their potential applications to mobile antennas. The first two research reports deal with the design of metamaterials and microwave and optical devices based on electromagnetic analysis using the topology optimization method. These techniques seem set to become a promising design procedure for metamaterials in the future. The subsequent two research reports describe metamaterial-based leaky-wave antennas for millimeter-wave radar systems and small antennas for mobile communications. The industry is hoping that the proposed antennas will find multiple uses in future automotive electronics devices.

In **Chapter 2** of this review, we introduce the



EMC : Electromagnetic compatibility

Fig. 1 Automotive applications of metamaterials.

trends in research related to metamaterials, while in **Chapter 3**, we overview the research being undertaken into metaterials at Toyota Central R&D Labs. In particular, we describe the topology design optimization for metamaterials and promising new types of metamaterial-based antenna.

2. Trends in research into metamaterials

2. 1 Historical milestones

The theoretical possibility of double negative (DNG) materials was first considered by Veselago in 1968.1) He predicted the existence of DNG materials and that they would exhibit unusual properties such as an inverted Snell's law, Doppler effect, and Vavilov-Cherenkov radiation. Pendry introduced metallic structures with negative permeability,2) and developed periodic non-magnetic structures for metallic split-ring resonators (SRRs).3) Smith fabricated an artificial metamaterial, which consisted of metallic wire strips and SRRs, and was the first to experimentally illustrate the existence of DNG materials.4-6) However, the resonant-type medium with its wire strips and SRRs was lossy and could only offer a narrow bandwidth. In 2002, Caloz et al.7) and Iyer and Eleftheriades8) proposed a transmission-line (TL) approach for metamaterials. These TL structures are circuit-oriented and non-resonant, and offer less loss and broader bandwidth. In particular, composite right/left-hand (CRLH) materials were proposed as a practical device for microwave and millimeter-wave applications of metamaterials.9, 10) Recently, many researchers have been rising to the challenge of scaling metamaterials to optical wavelengths. In 2000, Pendry indicated that a negative index lens could refocus both near and far fields, and was not subject to the diffraction limit of optics.11) He named this lens the "superlens." In 2005, Shalaev et al. experimentally demonstrated photonic metamaterials using metal rods that were fabricated using 1.5-micron infrared light.12, 13) In 2005, Blaikie et al. experimentally demonstrated super-resolution in an optical system using a very thin layer of metallic silver that acts as a superlens.14) A metal can have negative permittivity at optical wavelengths. It has been shown that metamaterials can be fabricated at the optical wavelength. However, the performance of these photonic metamaterials is insufficient, due to losses in the metal. Metals behave less like conductors at optical wavelengths.

2. 2 Metamaterial-based components and devices

Recent research into metamaterials has lead to the realization of promising new types of electromagnetic components and devices. By running two one-dimentional CRLH transmission lines in parallel, Caloz et al. discovered enormously tight coupling up to 0 dB of backward coupling for a broad frequency range up 35 % with an extremely small coupling length.15) A zero-order resonator using CRLH is characterized by its resonant frequency and Q factor being independent of the physical size of the resonator.16) A left-handed (LH) leaky-wave antenna (LWA) is an artificial antenna that supports backward waves. The beam can be continuously scanned from the back-fire to end-fire directions.17, 18) By inserting a varactor diode, this antenna can be configured to perform fixed-frequency electronic scanning.19) Small patch antennas based on CRLH transmission-line structures and SRRs have recently been built.20-23) Two-dimensional mushroom electromagnetic band-gap (EBG) structures24, 27) have been integrated with patch antennas to provide enhanced performance due to the band-gap of surface-wave suppression. They have also been used as the ground plane of wire antennas to achieve a low profile.25, 26) In the near future, we expect to see many optical device application developments using metamaterials.

3. Research at Toyota Central R&D Labs.

3. 1 Topology design optimization for electromagnetic materials

In the past, analytical models or equivalent circuit models have been used in the basic design of the metamaterials used in SRRs and CRLH transmission lines. In addition, electromagnetic simulation techniques, such as the moment method, the finite element method and the finite-difference time-domain method can also be utilized in the detailed design. However no general material design procedure has been pursued for the design of volumetric materials.

Topology optimization is the most flexible optimization method that can simultaneously deal with geometric and topological configuration changes.[28) In this method, a fixed design domain is defined such that it is larger than the obtained design. In a fixed domain, an arbitrary configuration can be expressed using a characteristic function, allowing large changes in the geometric and topological design during the optimization process. Topology optimization was originally developed for structural design, and recently adapted for many other types of design considering different branches of physics, such as electromagnetics.[29) These efforts were focused on electrostatics[30) and static magnetics.[31) In 2003, Kiziltas et al. proposed an attractive topology design optimization method for dielectric substrates to improve the bandwidth of microstrip antennas.[32) In 2004, Sigmund designed a photonic crystal structure by using topology optimization.[33) Toyota Central R&D Labs. has applied topology design optimization to the design of electromagnetic materials.[34-36) We expect that the topology optimization technique will also produce a significant breakthrough in the field of the design of metamaterials at the microwave, millimeter-wave and optical wavelengths.

We have been developing a novel method for designing the periodic microstructures of electromagnetic materials by using topology optimization. Moreover, the method can also be applied to the optimization of multi-physical functional materials. A flowchart of the optimization algorithm is shown in **Fig. 2**. We have three-field numerical solvers for electromagnetic, structural and thermal analysis using the finite element method. The adjoint variable method is introduced for the sensitive method.[37) The design algorithm used for the variable change method is based on the density method. The main feature involves representing the shape of a structure by the density of its micropore to allow the free transformation of the topology of the shape. A region in which the micropores are dense is treated as being empty. On the other hand, if the micropores are sparse, the region is regarded as being made of the given material. A region having an intermediate micropore density will have intermediate characteristics. The density of the material is translated to gradual changes in the physical properties such as the stiffness, weight or electromagnetic permittivity. Then, the density distribution is optimized for the desired specification by applying a mathematical non-linear programming technique. In the case of electromagnetic permittivity, the property of the material usually depends on variable density ρ, where ρ is related to the actual dielectric constant of the materials. The material property varies from $\rho = 1$ (dielectric relative permittivity of material $\varepsilon_r = 10$) to $\rho = 0$ (dielectric relative permittivity of air $\varepsilon_{r0} = 1$). By dividing the volume into design cells, the material property of each cell is controlled simultaneously in each iteration step and updated using the algorithm shown in Fig. 2 to reach a final design. The microstructure is represented by the material properties in every cell via density variable ρ. This approach is very attractive because of its simplicity and efficiency.

An example of a periodic electromagnetic band-gap dielectric material designed using topology optimization is shown in **Fig. 3**. The initial design is of a homogenous material in which the relative permittivity ε_r is 10. From Fig. 3, we can see that the microstructure is generated as an iteration step progresses and finally either a void or a filled/solid material is produced. Topology optimization is expected to produce new metamaterial microstructures with a specific band-gap, or double-

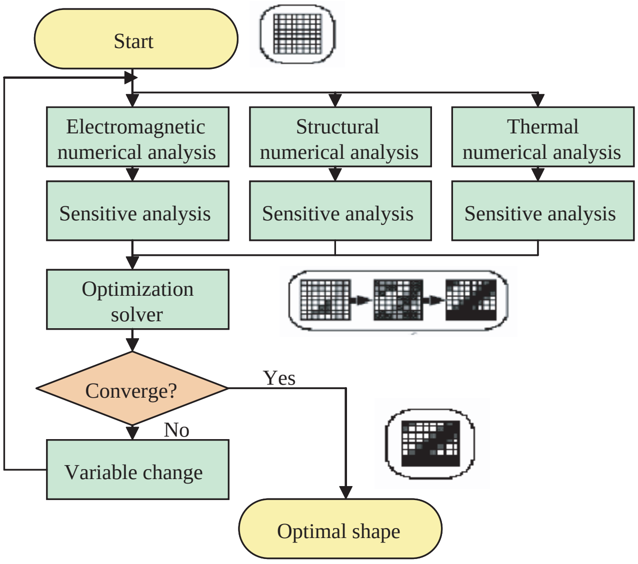


Fig. 2 Flowchart of topology optimization design.

negative materials. Problems to be solved in the future include the development of topology optimization techniques for metallic materials in electromagnetics, as well as multi-physical optimization algorithms. These techniques offer great promise for the design of metamaterials in the future.

3. 2 Left-handed leaky-wave antenna for millimeter-wave applications

There is currently greatly increased interest in the development of automotive radar sensors for adaptive cruise control and pre-crash safety systems, using a millimeter-wave band from 76 to 77 GHz.[38) For these systems, a field of view (FOV) with a length of 150 m, covering about 20° is sufficient, and this can be provided by most sensors on the market today. In contrast, new developments like "stop & go" adaptive cruise control and collision avoidance assist systems require the observation of a broader FOV up to 60°, with a maximum range of 60 m to allow them to deal with cut-in situations.39) An electronically scanned composite right/left-hand (CRLH) leaky-wave (LW) antenna using varactor diodes has been presented.19) This antenna has the advantage of wide beam scanning performance at a fixed frequency, but the diodes are too lossy to use in the millimeter-wave band. We are proposing a novel structure for a frequency-independent steerable CRLH LW antenna for the millimeter-wave band applications.40-42) This antenna offers the advantages of wide beam scanning, high gain and a simple structure in the millimeter-wave band. The proposed antenna features a movable dielectric slab that is placed above the CRLH LW antenna, and a radiation angle that can be steered by changing the distance between the slab and the antenna using compact actuators. **Figure 4** shows the structure of the proposed CRLH LW antenna with a movable dielectric slab. The CRLH LW antenna consists of series-connected unit cells that use simple gap capacitors and symmetrical straight shunt stubs. The dielectric slab is placed close to the CRLH LW antenna, and the effective dielectric constant is varied by changing the distance *h* between the microstrip line patterns and the dielectric slab, such that the radiation angle can be steered at the fixed frequency. The prototype CRLH LW antenna shown in **Fig. 5** was fabricated and tested in the

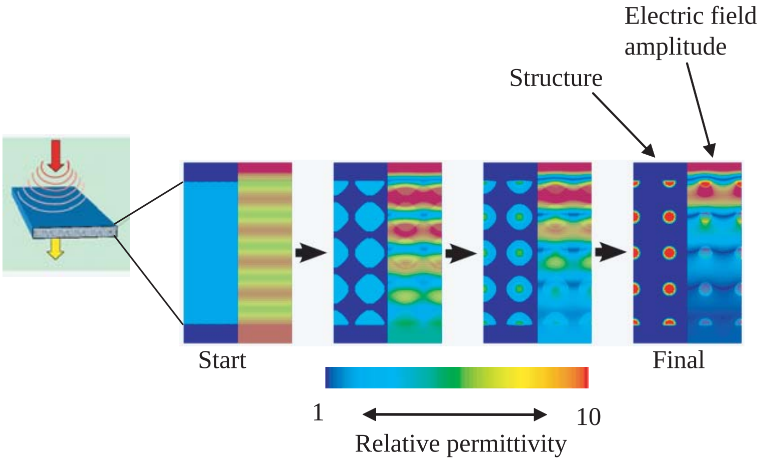


Fig. 3 Example of electromagnetic band-gap structure using topology optimization design.

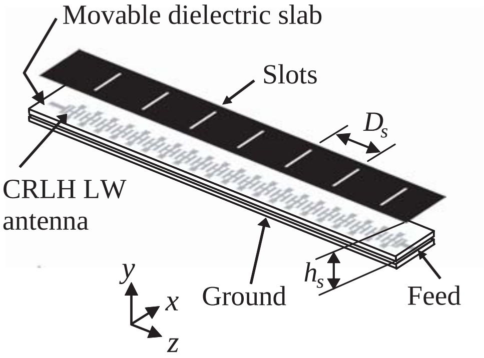


Fig. 4 Structure of 21-element steerable CRLH LW antenna with movable dielectric slab for (slots interval D_s = 1.8 mm, distance between slots and CRLH LW antenna h_s = 1.5 mm).

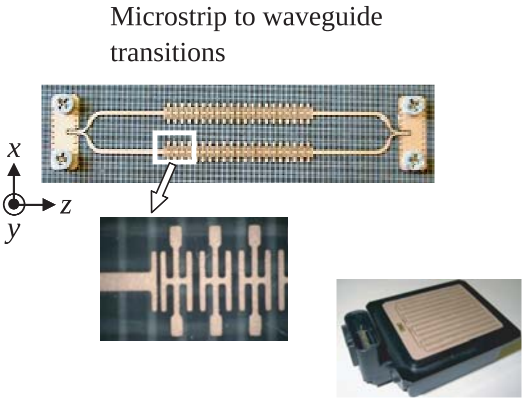
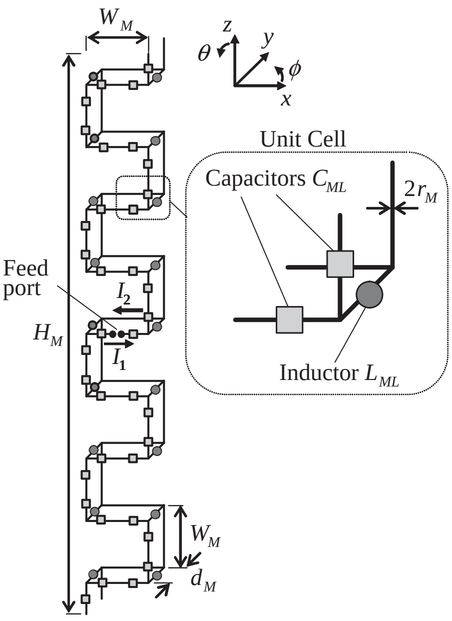


Fig. 5 Photographs of prototype antenna.

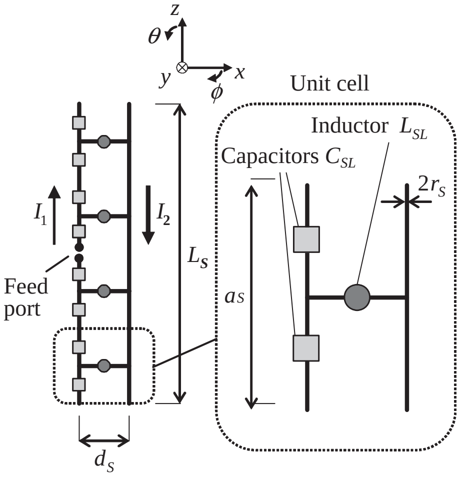
millimeter-wave band. A Teflon substrate was used as the movable slab. Its relative dielectric constant was 2.2, and its thickness was 0.127 mm. Moreover, slots have been added to the CRLH LW antenna to control the aperture amplitude distribution of the array antenna, so as to enhance the antenna gain. Backward-to-forward beam scanning characteristics at 76 GHz were demonstrated successfully by measurement. In the near future, it may be possible to realize automotive radar antenna systems with a high gain in excess of 20 dBi by using the proposed antenna. We believe that the LHLWA is a promising design for automotive millimeter-wave applications.

3. 3 Left-handed dipole antenna

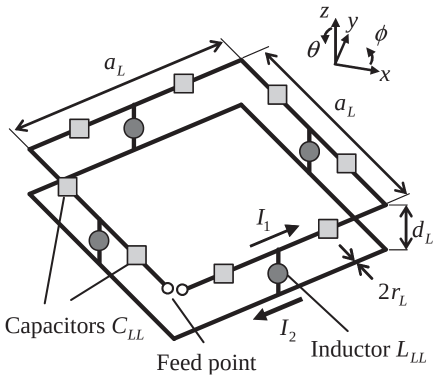
A new concept for forming a dipole antenna using a left-handed transmission line is proposed. The antenna is composed of a ladder network periodic structure of unit cells, each constructed using series capacitors and shunt inductors. Adding capacitors to one side of the network leads to out of phase currents with different amplitudes that produce high levels of radiation. The antenna has a unique feature in that the wavelength falls together with the frequency. The concept is applied to three antennas. The first is a small dipole, shown in **Fig. 6** (a), whilst working in the n = -1 mode, based on conventional resonance numbering.[43] A dipole with a length of 0.18 wavelengths can have an input impedance of 50 ohms. The second is an orthogonally polarized dipole, shown in Fig. 6 (b).[44] A left-handed meandered dipole using a higher order mode produces a polarisation that is orthogonal to that of a conventional right-handed one. The third is an omnidirectional loop, shown in Fig. 6 (c).[45] The loop has a one-wavelength circumference and produces an omnidirectional pattern in the plane of the loop, whilst using the zeroth mode. In contrast, a conventional right-handed loop produces a figure of eight pattern. We used numerical analysis to confirm that the proposed concept significantly



(b) Configuration of the meandered left-handed dipole antenna.



(a) Configuration of the straight left-handed dipole antenna.



(c) Configuration of the left-handed loop antenna.

Fig. 6 Left-handed wire antennas.

extends the design degrees of freedom for wire antennas. These proposed novel concepts for reducing the antenna size and enhancing the antenna performance offer great promise for future automotive mobile communications.

The results of one experimental study showed that loss remains a problem in left-handed wire antennas. The establishment of low loss designs for loaded inductors and capacitors is an important topic for further study.

4. Conclusion

In this review, recent trends in metamaterials have been overviewed, and we have also described topology design optimization for electromagnetic materials and a left-handed leaky-wave antenna for millimeter-wave applications and left-handed dipole antennas, all of which have been the subject of recent metamaterial studies at Toyota Central R&D Labs. Metamaterials should open up a whole new field for automotive electronics applications

References

1) Veselago, V. G. : "The Electrodynamics of Substances with Simultaneously Negative Values of ε and μ", Sov. Phys. Usp., **10**-4(1968), 509-514
2) Pendry, J. B., et al. : "Extremely Low Frequency Plasmons in Metallic Microstructures", Phys. Rev. Lett., **76**-25(1996), 4773-4776
3) Pendry, J. B., et al. : "Magnetism from Conductors and Enhanced Nonlinear Phenomena", IEEE Trans. Microwave Theory Tech., **47**(1999), 2075-2084
4) Smith, D. R., et al. : "Composite Medium with Simultaneously Negative Permeability and Permittivity", Phys. Rev. Lett., **84**-18(2000), 4184-4l87
5) Smith, D. R. and Kroll, N. : "Negative Refractive Index in Left-handed Materials", Phys. Rev. Lett., **85**-14(2000), 2933-2936
6) Shelby, R. A., et al. : "Experimental Verification of a Negative Index Refraction", Science, **292**(2001), 77-79
7) Caloz, C., et al. : "Transmission Line Approach of Left-handed (LH) Materials", USNC/URSI Nat. Radio Sci. Meet., **1**(2002), 39
8) Iyer, A. K. and Eleftheriades, G. V. : "Negative Refractive Index Metamaterials Supporting 2-D Waves," IEEE MTT-S Int. Microwave Symp. Dig., **2**(2002), 1067-l070
9) Caloz, C. and Itoh, T. : "Transmission Line Approach of Left-handed (LH) Materials and Microstrip Implementation of an Artificial LH Transmission Line", IEEE Trans. Antennas Propagat., **52**(2004), 1159-1166
10) Sanada, A., et al. : "Characteristics of the Composite Right/Left-handed Transmission Lines", IEEE Microwave Wireless Comp. Lett., **14**(2004), 68-70
11) Pendry, J. B. : "Negative Refraction Makes a Perfect Lens", Phys. Rev. Lett., **85**-18(2000), 3966-3969
12) Shalaev, V. W., et al. : " Negative Index of Refraction in Optical Metamaterials", Opt. Lett., **3356**(2005), 30-24
13) Dolling, G., et al. : "Simultaneous Negative Phase and Group Velocity of Light in a Metamaterial", Science, **312**(2006), 890-894
14) Melville, D. O. S. and Blaikie, R. J. : "Super-Resolution Imaging through a Planar Silver Layer", Opt. Express, **13**(2005), 2127-2134
15) Caloz, C., et al. : "A Novel Composite Right/Left-handed Coupled-line Directional Coupler with Arbitrary Coupling Level and Broad Bandwidth", IEEE Trans. Microwave Theory Tech., **52**(2004), 980-992
16) Sanada, A. : "Zeroth Order Resonance in Composite Right/Left-handed Transmission Line Resonators", Asia-Pacific Microwave Conf., **3**(2003), 1588-1592
17) Grbic, T. and Eleftheriades, G. V. : "A Backward-wave Antenna Based on Negative Refractive Index L.-C Networks", IEEE AP-S Int. Antenna Propagat. Symp. Dig., **4**(2003), 340-343
18) Lei, L., et al. : "Dominant Mode Leaky-wave Antenna with Backfire-to-endfire Scanning Capability", Electron. Lett., **38**-23(2002), 1414-1416
19) Lim, S., et al. : "Electronically-controlled Metamaterial-based Transmission Line as a Continuous-scanning Leaky-wave Antenna", IEEE MTT-S Int. Microwave Symp., (2004)
20) Sanada, A., et al. : "A Planar Zeroth Order Resonator Antenna Using a Left-handed Transmission Line", European Microwave Conf., (2004)
21) Lee, C., et al. : "Design of Resonant Small Antenna Using Composite Right/Left-handed Transmission Line", Proc. IEEE Antennas Propagat. Soc. Int. Symp., **2B**(2005), 218-221
22) Qureshi, F., et al. : "A Compact and Low-profile Metamaterial Ring Antenna with Vertical Polarization", IEEE Antennas and Wireless Propagat. Lett., **4**(2005), 333-336
23) Sarabandi, K. and Mosallaei, H. : "Embedded-circuit Meta-materials for Novel Design of Tunable Electro-ferromagnetic Permeability, Band-gap, and Bi-anisotropic Media", IEEE AP-S Int. Antenna Propagat. Symp. Dig., (2003)
24) Sievenpiper, D. : "High-impedance Electromagnetic Surfaces with a Forbidden Frequency Band", IEEE Trans. Microwave Theory Tech., **47**(1999), 2059-2074
25) Yang, F. and Rahmat-Samii, Y. : "A Low Profile Circularly Polarized Curl Antenna over Electromagnetic Band-gap (EBG) Surface",

Microwave Opt. Technol. Lett., **31**-3(2001), 165-168
26) Nakano, H., et al. : "Effects on the Radiation Characteristics of Using a Corrugated Reflector with a Helical Antenna and an Electromagnetic Band-gap Reflector with a Spiral Antenna", IEEE Trans. on Antennas and Propagat., **53**-1(2005), 191-199
27) Sanada, A. : "Planar Distributed Structures with Negative Refractive Index", IEEE Trans. Microwave Theory Tech., **52**-4(2004), 1252-1263
28) Bendsøe, M. P. and Kikuchi, N. : "Generating Optimal Topologies in Structural Design Using a Homogenization Method", Computer Methods in Appl. Mech. and Eng., **71**(1988), 197-224
29) Dyck, D. N. and Lowther, D. A. : "Automated Design of Magnetic Devices by Optimizing Material Distribution", IEEE Trans. Magnetics, **32**-3 (1996), 1188-1193
30) Byun, J.-K., et al. : "Topology Optimization of Electrostatic Actuator Using Design Sensitivity", IEEE Trans. on Magnetics, **38**-2(2002), 1053-1056
31) Yoo, J., et al. : "Structural Optimization in Magnetic Devices by the Homogenization Design Method", IEEE Trans. on Magnetics, **36**-3(2000), 574-580
32) Kiziltas, G., et al. : "Topology Design Optimization of Dielectric Substrates for Bandwidth Improvement of a Patch Antenna", IEEE Trans. on Antennas and Propagat., **51**-10(2003), 2732-2743
33) Sigmund, O. and Jensen, J. : "Systematic Design of Photonic Crystal Structure Using Topology Optimization: Low-loss Waveguide Bends", Appl. Phys. Lett., **84**-12(2004), 2022-2024
34) Nomura, T., Sato, K., Hirayama, K. and Nishiwaki, S. : "Topology Optimization of Periodic Microstructure of Electromagnetic Material", 6th World Congr. of Struct. and Multidisciplinary Optim. (WCSMO6), No.981(2005), Int. Soc. for Structural and Multidisciplinary Optimization
35) Nomura, T. and Sato, K. : "Topology Design Optimization of Dielectric Resonator Antenna Using Finite-difference Time-domain Method", IEEE AP-S Int. Antenna Propagat. Symp., (2006), 1317-1320
36) Nomura, T., et al. : "Topology Optimization for the Structural Design of Antennas Using Finite Difference Time Domain Technique", Proc. of 7th World Congr. of Computational Mechanics, **1357**(2006)
37) Hang, E. and Arora, S. : "Design Sensitivity Analysis of Elastic Mechanical Systems", Computer Methods in Appl. Mech. and Eng., **15**(1978), 35-62
38) Tokoro, S., et al. : "Electronically Scanned Millimeter-wave Radar for Pre-crash Safety and Adaptive Cruise Control System", Proc. IEEE Intell. Veh. Symp., (2003), 304-309
39) Rasshofer, R. H., et al. : "77 GHz Long Range Radar Systems Status, Ongoing Developments and Future Challenges," Proc. 2nd Euro. Radar Conf., (2005), 161-164
40) Matsuzawa, S., et al. : "A W-band Microstrip Composite Right/Left-handed Leaky Wave Antenna", IEICE Trans. Commun., **E89**-B-4(2006), 1464-1466
41) Sato, K., et al. : "Electronically Scanned Left-handed Leaky Wave Antenna for Millimeter-wave Automotive Applications", Int. Workshop Antenna Tech. Proc., (2005),420-424
42) Matsuzawa, S., et al. : "W-band Steerable Composite Right/Left-handed Leaky Wave Antenna for Automotive Applications", IEICE Trans. Commun., **E89**-B-9(2006), 1337-1344
43) Iizuka, H. and Hall, P. S. : "A Left-handed Dipole Concept", Proc. Int. Workshop on Antenna Tech., (2006), 396-399
44) Iizuka, H. and Hall, P. S. : "Omnidirectional Left Handed Loop Antenna", Proc. IEEE Antennas Propagat. Soc. Int. Symp., **1**(2006), 27-30
45) Iizuka, H. and Hall, P. S. : "Orthogonally Polarised Dipole Antenna Using Left Handed Transmission Lines", Proc. 36th Euro. Microwave Conf., (2006)

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The publisher apologizes for the following omission.
It was corrected as of Jan. 23, 2007.
p.8 <Author introduction : Kazuo Sato>
<Added> Academic degree : Dr. Eng.