Review

Research Trends in Metamaterials

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メタマテリアルの研究動向

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Abstract

Metamaterials are a new class of ordered composites that exhibit exceptional electromagnetic properties not readily observed in nature. In particular, artificial materials with both negative permittivity and permeability have attracted widespread interest in recent years. These composites are constructed from an array of metallic in dielectric and magnetic substrates and exhibit unusual electromagnetic properties such as inverted Snell's law and Doppler shift behavior within a particular frequency range. Recent research activities in the field of metamaterials have not only demonstrated interesting physical phenomena but also lead to the development of design procedures and the realization of promising new microwave and millimeter-wave components and devices. A promising technique for the creation of new electromagnetic materials is topology design optimization. Significant research efforts have led to the development of microwave and millimeter-wave applications of metamaterials such as couplers, resonators, negative refractive index lenses, small antennas, backfire-to-endfire leaky-wave antennas, and absorbers. These new metamaterials should open up a new field of future automotive applications, such as beam steering antenna systems for radar and mobile communication, novel magnetic materials for electric motors, and high-performance absorbing and shielding materials for electromagnetic compatibility. In this review, we survey metamaterials in microwave and millimeter-wave applications. In addition, we present recent R&D activities of our laboratory in the field of metamaterials.

Keywords: Metamaterials, Microwave, Millimeter-wave, Antennas, Topology optimization, Finite element method

要　旨

メタマテリアルは，自然界にはない優れた特性を示す複合材料である。特に，近年，負の誘電率と透磁率を有する人工的に作られた材料が注目されている。これら材料は誘電体もしくは磁性体の中に金属導体を配列して構成され，特定の周波数において従来のスネルの法則やドップラーの法則とは反対の興味深い電磁気特性を有する。最近の研究では，このような物理現象の証明だけではなく，メタマテリアルの材料構造設計技術や，マイクロ波・ミリ波帯でのコンポーネント，デバイスの実現にも目が向けられつつある。設計手法としては，電磁材料のトポロジー最適設計技術は，将来有望な手法の一つである。一方，応用技術としては，マイクロ波・ミリ波帯での結合器，共振器，バンドギャップ構造材料を用いた負屈折レンズ，小型アンテナ，ビーム走査漏れ波アンテナ，電波吸収体などの開発が現在積極的に進められている。これらの新しいメタマテリアルは，自動車レーダシステムや移動体通信システムのビーム走査アンテナシステム，電気自動車のための新しい磁性材料，そしてEMC（ 電磁両立性 ）のための電磁波吸収・遮へい材料など，将来の自動車エレクトロニクス応用にとって大変に魅力があるものと言える。ここでは，マイクロ波・ミリ波帯におけるメタマテリアルの研究動向と，当社におけるメタマテリアルに関する研究の取り組みについて述べる。

キーワード　メタマテリアル，マイクロ波，ミリ波，アンテナ，トポロジー最適化，有限要素法

1. Introduction

Metamaterials are a new class of ordered composites that exhibit exceptional electromagnetic properties not readily observed in nature. Recently, there has been an increasing interest in the development of metamaterials, such as double negative (DNG) materials, i.e., artificial materials with both negative permittivity and permeability; electromagnetic band-gap (EBG) structured materials, and complex surfaces. DNG materials are now known under several categories including left-handed (LH) materials, negative index of refraction (NIR) materials, and others.

The theoretical possibility of DNG materials was first considered by Vesalago in 1968.[1] He posed DNG materials and predicted they would exhibit unusual properties such as inverted Snell's law, Doppler shift and Cherenkov radiation. Pendry introduced metallic structures with negative permeability,[2] and developed the periodic nonmagnetic structures known as metallic split-ring resonators (SRRs) as shown in **Fig. 1**(a) in 1999.[3] Smith fabricated an artificial metamaterial composed of metallic wire strips and SRRs as shown in Fig. 1(b) and tested the DNG materials experimentally for the first time.[4-6] However, the resonant-type medium using wire strips and SRRs is lossy and has narrow bandwidth. In 2002, Caloz et al.[7] and Iyer and Eleftheriades[8] proposed a transmission-line (TL) approach for metamaterials. The TL structures are circuit oriented and non-resonant, and provide less loss and broader bandwidth. In particular, the composite right/left-hand (CRLH) materials shown in Fig. 1(c) were proposed as a practical metamaterial device for microwave and millimeter-wave applications.[9-10] Recent research activities on metamaterials have not only demonstrated interesting physical phenomena but also lead to the development of design procedures, and the realization of new electromagnetic components and devices.

Usually, analytical models or equivalent circuit models are used in the basic design of the SRRs and the CRLH transmission line. 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 in the design of volumetric materials. Kiziltas et al. proposed an attractive topology design optimization procedure for dielectric substrate to improve the bandwidth of microstrip antennas in 2003.[11] Toyota Central R&D Labs. have applied topology design optimization to the design of electromagnetic materials.[12] Techniques such as these show promise for design of metamaterials in the future.

From another perspective, significant research efforts have progressed the development of microwave and millimeter-wave applications of metamaterials such as couplers,[13] resonators,[14] NIR planar lenses using EBG structures (Fig. 1(d)),[15, 16] small antennas,[17, 18] backfire-to-endfire leaky-wave antennas (Fig. 1(e)),[19-22] and absorbers.[23]

We believe that these new electromagnetic components and devices will prove useful for future automotive electronics applications as shown in **Fig. 2**. Future radar and mobile communication systems will need to be inexpensive and compact

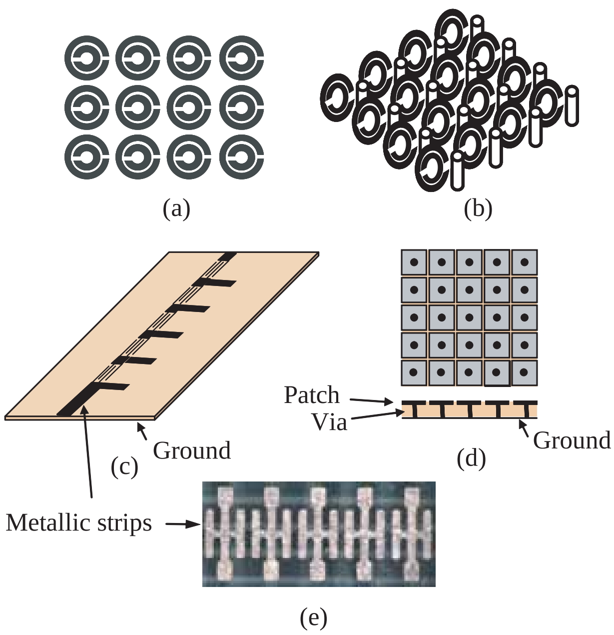

Fig. 1 Typical configurations of metamaterials. (a) Split ring resonators, (b) Metallic wire strips and split ring resonators, (c) Composite right/left-hand transmission line, (d) Electromagnetic band-gap (EBG) structure, (e) Millimeter-wave left-handed leaky wave antenna developed by Toyota Central R&D Labs.

and will be based on beam steering antennas. In electric vehicles, novel high-performance magnetic materials for electric motors and high-performance absorbing and shielding materials for electromagnetic compatibility are strongly needed.

In this review, we introduce a novel topology design optimization procedure for electromagnetic materials (Chap. 2)[12] along with microwave and millimeter-wave metamaterial applications (Chap. 3). In particular, a promising new type of left-handed (LH) leaky-wave antenna (LWA) is described which utilizes CRLH materials for millimeter-wave applications.[22]

2. Topology design optimization for electromagnetic materials

Metamaterials usually have a periodic internal microstructure and reveal extraordinary characteristics which have not been found in nature. It is usually difficult to predict the topology of these microstructures even though they tend to have simple shapes. Topology optimization techniques are considered to be advantageous for designing new metamaterials. To design the microstructure of materials, we adopt a topology optimization method that can select the best geometric and topological configuration while taking into account the material composition. Topology optimization has already achieved successes in finding extremal material structures in structural mechanics applications such as elastics, thermoelastics or piezoelastics. We expect that topology optimization techniques will also lead to significant breakthroughs in the field of metamaterials for microwave and millimeter-wave frequency devices.

In design optimization for electromagnetics, there have been several studies on topology optimization for magneto-static applications,[24] photonic band-gap wave-guides,[25] and for the dielectric substrates of microstrip antennas.[12] We have been developing a novel design method to give periodic microstructure of electromagnetic materials using topology optimization. Moreover, the method can optimize multi-physical functional materials. The design method and an example of an electromagnetic band-gap dielectric material designed by the method are introduced below.

A flowchart of the optimization algorithm is shown in **Fig. 3**. We adopt three field numerical methods for electromagnetic, structural and thermal analysis using the finite element method. The adjoint variable method is introduced as sensitivity analysis.[26] The density method is utilized as the design algorithm. The main idea is to represent the shape of the structure by the density of micropores to allow free transformation of the topology. A region where the micropores are dense is treated as

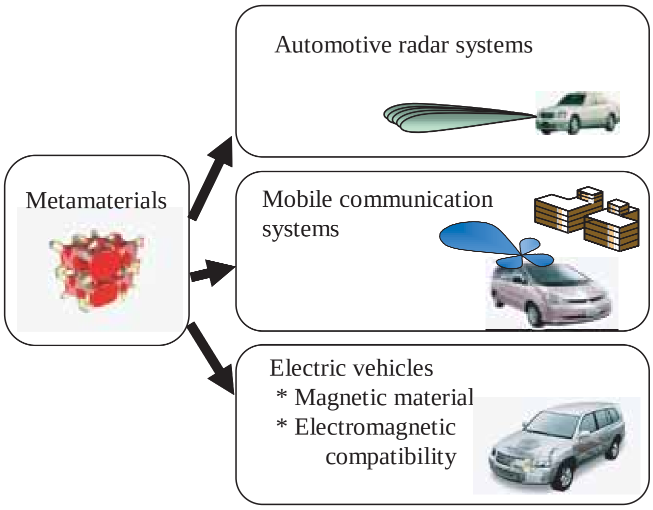

Fig. 2 Microwave and millimeter wave applications of metamaterials.

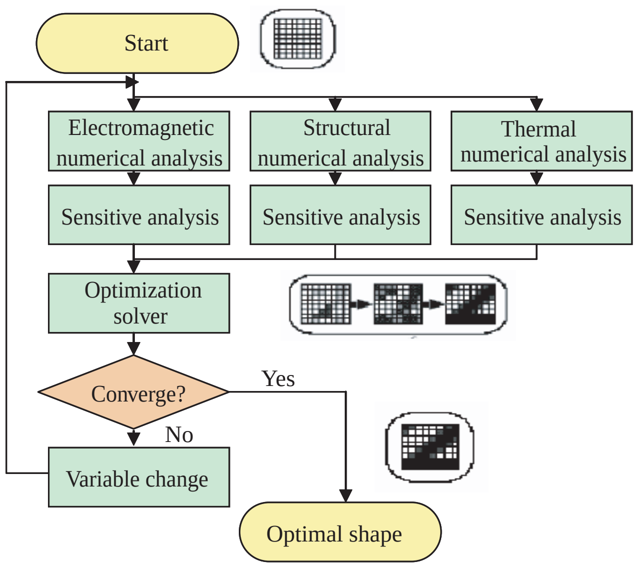

Fig. 3 Flowchart of topology optimization design.

empty. In contrast, if the micropores are sparse, the region includes the given material. A region with an intermediate micropore density will have intermediate characteristics. The density of the material is translated as a gradual change in the physical properties such as in stiffness, weight, or electromagnetic permittivity. Then the density distribution is optimized for the desired specifications by a non-linear programming technique. The electromagnetic property of the material usually depends on the variable density ρ, where ρ is related to the actual dielectric constant of the material. 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 cells, the material property of each cell is controlled simultaneously in each iteration step and is updated using the algorithm shown in Fig. 3 to reach a final design. The microstructure is represented by material property at every cell via a 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 by the topology optimization method is shown in **Fig. 4**. The initial design conditions define a homogenous material in which the relative permittivity ε_r is 10. It can be seen from Fig. 4 that the microstructure progresses with each iteration step and finally generates either a void or a filled/solid material. Topology optimization is expected to be able to design new metamaterial microstructures with desired band-gap or double negative properties. Future developments should investigate topology optimization techniques for metallic materials in the design of electromagnetics and multi-physical functional materials.

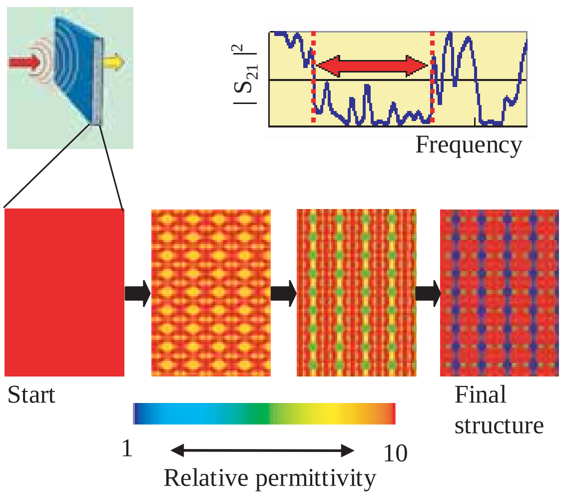

Fig. 4 Example of electromagnetic band-gap structure using topology optimization design.

3. Microwave and millimeter-wave metamaterial applications

3. 1 Overview

Recent research activities into metamaterials have realized promising new electromagnetic components and devices. In this section, we first introduce the significant research efforts put towards microwave and millimeter-wave components and devices.

By running two one-dimensional composite right/left-hand (CRLH) transmission-lines in parallel, Caloz et al. have discovered massively tight coupling of up to 0 dB for backward coupling over a broad frequency range up to 35% with extremely small coupling lengths.[13)] A zero-order resonator using CRLH has been constructed with the feature that the resonant frequency and Q factor are independent of the physical size of the resonator.[14)] Another application is the left-handed (LH) leaky wave antenna (LWA), which is an artificial antenna which supports backward waves. The beam can be continuously scanned from back-fire to end-fire directions.[19, 20)] By inserting a varactor diode, this antenna has been changed to a fixed-frequency electronically scanned device.[21)] Also, small patch antennas based on CRLH transmission-line structures and SRRs have recently been built.[17, 18)] Two-dimensional mushroom electromagnetic band-gap (EBG) structures have been integrated with patch antennas to provide enhanced performance, utilizing the band-gap for surface-wave suppression.[15)] These structures have also been used as the ground plane of wire antennas to achieve a low profile.[27, 28)] In addition, the two-dimensional EBG structures have been used as frequency-scanned conical beam antennas and negative index of refractions (NIR) planar lenses.[16)] Finally, absorbers,[23)] frequency selective surfaces, and high impedance surfaces based on metamaterials are being studied.[15)]

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

A wave in which the phase velocity and group velocity have opposite signs is known as a backward wave. The left-handed (LH) leaky wave antenna (LWA) is an artificial antenna which supports backward waves. LH LWAs consisting of a sequence of unit cells with a series capacitance and a shunt inductance have been proposed for a device which is predicted to lead to new microwave applications due to its unique backward wave characteristics and intrinsically wider bandwidth and lower insertion loss compared with the resonant type.[8, 9] The concept of the composite right/left-handed (CRLH) antenna enables characterization and design of practical LH LWAs by including inevitable parasitic series inductances and shunt capacitances in the TL model.

In the past few years, there has been significant interest in radar systems for adaptive cruise control (ACC) using millimeter-waves from 76 GHz to 77 GHz. In the ACC system, the beam is scanned in the azimuth angle to detect targets even on a curved road.[29] In these millimeter-wave applications, an antenna with a planar structure offers the advantage of reduced fabrication cost. Although, much work has been reported on LH LWAs at microwave frequencies, no information can be found in the literature on printed LH LWAs at millimeter-wave frequencies. We have designed LH LWAs operating from 75 to 82 GHz and have confirmed beam scanning by simulation and experiments.

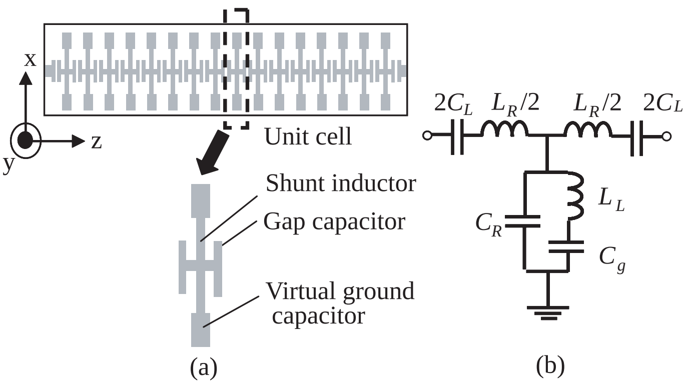

Fig. 5 Left-handed leaky wave antennas.
(a) Microstrip implementation
(b) Equivalent circuit of the unit cell

A conventional LH LWA for microwave applications consists of a series of interdigital capacitors and shunt stubs connected with vias to the ground as shown in Fig. 1(c). Manufacturing the interdigital capacitors and meander-line inductors to operate at millimeter-wave frequencies is very difficult because of the etching tolerance. For the millimeter-wave antenna, the value of capacitance and inductance becomes smaller than that of the microwave antenna, so the interdigital capacitor and the shunt meander-line inductor can be replaced with a simple gap capacitor and line inductor. We have designed a planar LH LWA for operation at a millimeter-wave frequency. In order to maximize the fabrication tolerance, we have chosen a via-free LH structure with a simple series gap and a straight shunt inductor connected to a virtual ground patch in the unit cell, which will contribute to reducing conductor losses as well.

The proposed LH LWA of microstrip line implementation and its equivalent circuit are shown in **Fig. 5**(a) and (b), respectively. The unit cell consists of a series gap capacitor and a shunt inductor connected to a metal patch. The gap capacitor provides a series capacitance C_L and a parasitic series inductance L_R . The shunt inductor provides a shunt inductance L_L and a parasitic capacitance C_R to the ground. The metal patch provides a capacitance C_g to the ground. When C_g is large, it provides the virtual ground voltage and the shunt circuit becomes inductive.[30] Under this condition, the LWA supports backward waves with series C_L and shunt L_L.

Dispersion characteristics based on the equivalent circuit are shown in **Fig. 6** for typical parameter values of L_L, C_L, L_R, and C_R. The figure reveals that, at lower frequencies, the signs of the phase velocities v_p and group velocities v_g are opposite ($v_p v_g = (\omega/\beta)\,(\partial\omega/\partial\beta) < 0$, where ω is the angular frequency and β is the wave number) and, therefore, the LWA supports backward waves (left-handed wave: LH waves). On the other hand, at higher frequencies, the signs of the phase and group velocities are the same ($v_p v_g > 0$) and the LWA supports forward waves (right-handed wave: RH waves). This LWA works as a balanced CRLH LWA with a seamless transition between the LH and RH modes without a band-gap between the two modes. In the LH and RH regions, leakages in the backward and forward directions occur and it operates as a backfire-to-endfire scanning antenna.

The radiation patterns of co-polarization for E_θ are shown in **Fig. 7**. Backward radiation and a beam scanning capability by changing frequency is observed in the LH frequency region, confirming the device supports backward waves. We have also confirmed beam scanning from 70 to 100 degrees by changing the frequency.

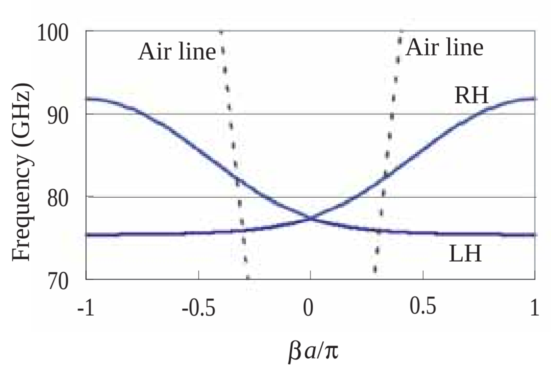

Fig. 6 Dispersion characteristics of the periodic structure of Fig. 5 (b)(L_L=0.1nH, L_R=0.06nH, C_L=0.07pF, C_R=0.8pF, C_g=0.045pF).

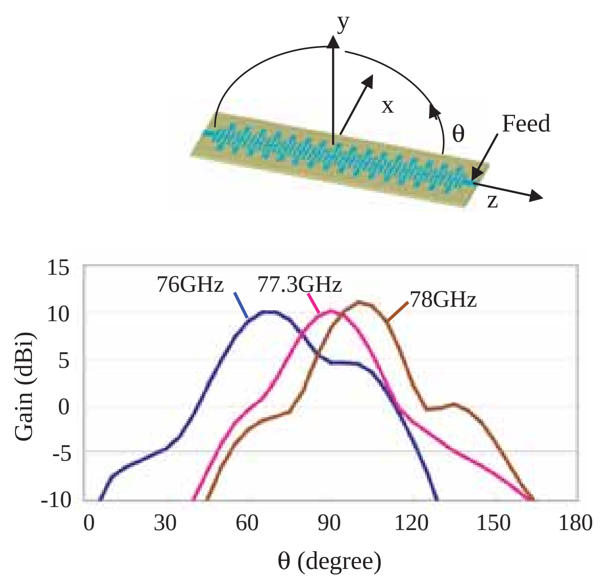

Fig. 7 Radiation pattern of the 16-cell backward to forward leaky-wave antenna (E_θ).

Moreover, for a millimeter-wave automotive radar system, we have been developing novel structure LHLWAs which can control the radiation angle for a fixed frequency. The antenna includes a dielectric material which locally changes its dielectric constant in response to an external stimulus. Liquid crystals have attractive properties such as smaller losses in the millimeter-wave band. We believe LHLWA materials are promising in antennas for automotive millimeter-wave applications.

4. Conclusion

In this review, we have outlined recent trends in metamaterials. In particular, a topology design optimization method for electromagnetic materials has been demonstrated by a left-handed leaky wave antenna for millimeter-wave applications, created in recent research on metamaterials at Toyota Central R&D Labs. Such metamaterials should open up a new field of microwave and millimeter-wave applications for automobiles.

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