Technology Trends in Microwave Propagation Design using Metamaterials

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[Summary] Metamaterials with an arrangement of metallic and dielectric materials at a shorter period than the wavelength of the target electromagnetic wave have specific electromagnetic-wave propagation properties not seen in nature. Recently, research on metamaterials that enable various propagations of microwaves and light has been progressing. Among them, research on the design of microwave propagation is a very wide field, especially on two-dimensional metasurfaces. This article outlines the negative refractive index typically characterizing metamaterials and summarizes a composite right/left-handed transmission line model as an analogy of propagation familiar to electronic engineers, finally introducing ongoing research into various applications.

1 Introduction

For the past 20 years, the unique reflection and transmission characteristics of electromagnetic wave by artificial structures consisting of metals and dielectrics arranged in a period sufficiently shorter than the wavelength of the target electromagnetic wave have been vigorously studied and applied. In the future, it is expected that basic research on such artificial structures, called metamaterials, and the practical application of their properties will be advanced.

On the other hand, in accordance with the recent huge and increasing demand for wireless communications services and applications, use of mmWave communications offering larger capacity and faster speeds is growing. Fifth-generation mobile communications systems (5G) are not only using the 6-GHz band but are also starting commercial services using the 28 and 39-GHz bands, with next-generation wireless LAN (WiGig) even using the 60-GHz band. Since free-space propagation losses at higher frequencies cannot be ignored, mmWave mobile communications systems require high-performance and high-function antennas with controllable directivity to suppress such losses. In fields other than communications, automotive radar and various wireless sensing networks for environmental monitoring, such as power saving and wireless feeds, are being commercialized as one basic technology for building an IoT-based society. To assure high sensitivity for aerospace and meteorological radar, there is increasing need to improve antenna gain and also control antenna patterns. In these circumstances, a so-called "smart" society must improve technologies for creating electromagnetic waves by implementing high-performance and high-function antennas, etc. Moreover, discussions are starting on development of sixth-generation (6G) systems for rollout in the 2030s with investigation of the 300-GHz frequency band required for even larger-capacity and higher-speed transmissions. Metamaterials are considered to be a fundamental technology for building these wireless networks with never-before-seen "Intelligent Surfaces".[1) to 3)]

Research on electromagnetic wave propagation in periodic structures, such as metamaterials, covers many fields and it is difficult to cover all of them here. Consequently, this article outlines negative refractive index typically characterizing metamaterials and summarizes a composite right/left-handed transmission line model as an analogy of propagation familiar to electronic engineers, finally introducing ongoing research into various applications.

2 Metamaterials

Artificial materials having a structure that is smaller than the target electromagnetic wavelengths and with properties not occurring in nature are called metamaterials. This article discusses these metamaterials with a negative refractive index. Artificial dielectrics were already known in 1948[4)] and Veselago proposed the theoretical existence of negative refractive index in 1964 and discussed optical propagation in negative-index media. Some 30 years later, attention turned to negative-index media again and Pendry et al. proposed in 1990 that negative-index media could be implemented in the microwave band.[6), 7)] Subsequently, in 2001, a negative-index medium with both a dielectric constant and magnetic permeability was demonstrated[9)] and research subsequently accelerated.[10) to 12)] Negative refractive index media (left-handed media) are only achievable using metamaterials.

Figure 1 shows the classification of media by polarity of the permittivity (ε) and magnetic permeability (μ). Since most media have a relative permittivity of about 1, they are classified in Groups I and II. Among these, dielectrics, such as glass and resins, have a positive permittivity (Group I). Since most metals have good conductivity in the microwave region, they have a permittivity that can be considered a purely imaginary number, and have a negative dielectric constant in the optical region (Group II). Although some magnetic materials have a negative magnetic permeability in the microwave region, but there are no known such materials that simultaneously have a negative permittivity (Group IV). In other words, many media permeable to microwaves have a positive permittivity and a relative permittivity around 1, then indicating a positive refractive index.

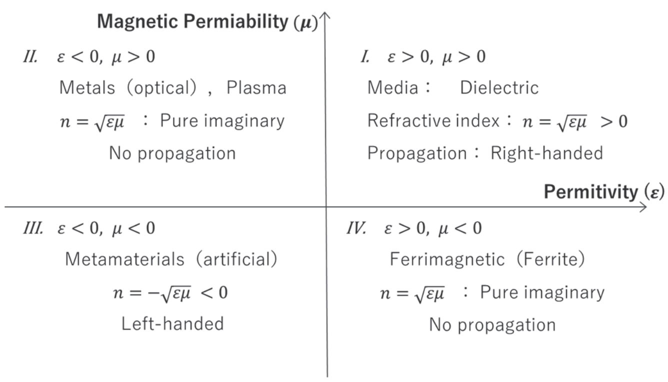


Figure 1 Media Classification by Polarity of Dielectric Constant (ε) and Magnetic Permeability (μ)

However, using artificial materials with a periodic structure that is sufficiently smaller than the target electromagnetic wavelengths, we can change the effective permittivity and magnetic permeability, and achieve negative permittivity and negative permeability in specific frequency bands. By desgning the periodic structure so as to overlap the frequency bands, it is possible to achieve the materials with both negative permittivity and negative permeability, and then negative refractive index (Group III).

The first negative index media were achieved by combining a fine metal wire array with a splitting resonator array as shown in Figure 2.[8)] As shown in Figure 2(a), it is known[6)] that aligning fine metal wires at an interval that is sufficiently smaller than the target wavelength creates negative permittivity for the polarized wave parallel to the wires in the microwave region. This phenomenon is explained based on free electron vibration. The frequency of the free vibration is called the plasma frequency and the medium has a negative permittivity below the plasma frequency as shown in Figure 2(a). The square of plasma frequency is inversely proportional to the effective electron mass and proportional to the effective electron density. It is known that metals such as silver have a plasma frequency in the ultraviolet region. Fine wires operating in a microwave field do not receive restitutive force like with free electrons at optical frequency (Drude model) but have a large effective mass due to inductance; due to the proportion of the fine wires in free space, the effective electron density can decrease much more than that of bulk metal in response to the microwave field. As a result, the effective plasma frequency of a fine metal wire array can be designed in the microwave band.

When a metal ring (inductor with single turn) is located in AC magnetic field, a current flows so as to reduce the interlinkage flux. Consequently, the flux density in the coil approaches zero, then a medium, which includes metal rings array with sufficiently smaller period than the wavelength of the electromagnetic wave, effectively has a relative permittivity of less than 1, because of the imhomogenius magnetic flux density. However, the magnetic permeability is positive because a antimagnetic field will not be stronger than the applied magnetic field. Therefore, when cutting the ring to make a gap, the gap becomes a capacitor and forms an LC resonator. This structure is called a split-ring resonator, and the current increases and generates a stronger antimagnetic field near the resonance frequency. Consequently, as shown in Figure 2(b), if a low loss split-ring resonator arranged with sufficient density, a negative magnetic permeability could be achieved in a frequency range at the higher frequency side than the resonance frequency.[7)] This simplified explanation uses the example of a simple single ring, but a double split ring with breaks at the opposite sides of the rings is commonly used to suppress the response to the electrical field.

As described above, combining a fine metal-wire array with a split-ring resonator as shown in Figure 2(c) generates a negative refractive index.

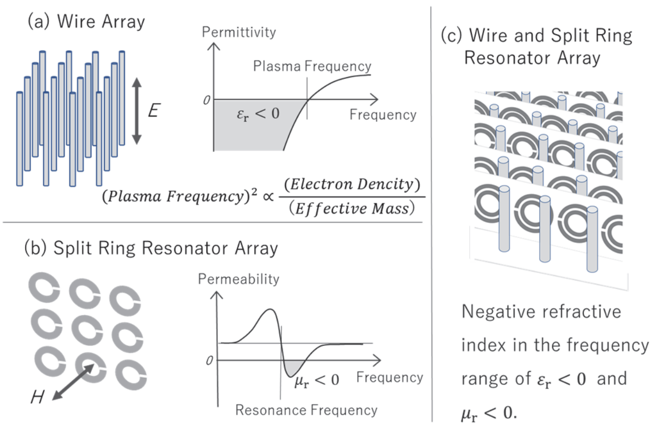


Figure 2 Metal Wire Array and Split-Ring Resonator Array

3 Composite Right/Left-Handed Transmission Line

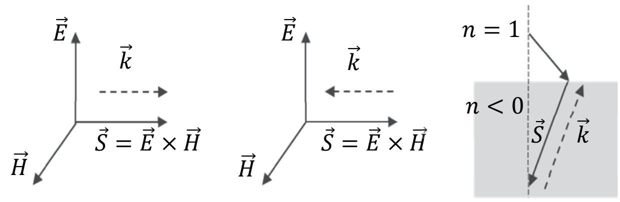
As described previously, the first negative index media were created using a combination of metal wires and split-ring resonators, but the resonance loss is large and the frequency band is narrow at a negative refractive index. Therefore, broadband, low loss, non-resonant left-handed media (negative index media) which are based on transmission line theory, have been proposed and their engineering applications are expanding.

The following section provides a simple explanation of improved left-handed media and introduces Composite Right/Left-Handed (CRLH) transmission line model as a description model of a metamaterial.

3.1 Left-Handed Media (Negative Index Media)

The propagation of electromagnetic waves in homogenous media is described by the dielectric constant and magnetic permeability. According to electromagnetic theory, the relationship between the planar-wave wave number $\vec{k}$, electrical field $\vec{E}$, and magnetic field $\vec{H}$, propagating in a medium is $\vec{k} \times \vec{E} = \omega\mu\vec{H}$, $\vec{k} \times \vec{H} = -\omega\varepsilon\vec{E}$. Since $\varepsilon > 0$, $\mu > 0$ in a vacuum (air) or normal dielectrics, the phase propagation direction (direction of wave number vector $\vec{k}$) is the direction in which right-handed screw goes when $\vec{E}$ is rotated toward $\vec{H}$ as shown in Figure 3(a). This type of medium is called right-handed. Conversely, when $\varepsilon < 0$, $\mu < 0$, the wave vector has the direction in which left-handed screw advances as shown in Figure 3(b), so this type of medium is called left-handed. Since the energy propagation direction at this time is in the pointing vector $\vec{S} = \vec{E} \times \vec{H}$ direction, with left-handed media the phase propagation direction $\vec{k}$ and the energy propagation direction $\vec{S}$ are in opposite directions. This type of medium where the phases advance in opposite directions is called a backward wave. Although difficult to understand intuitively, in the normal propagation state when the electromagnetic wave in the left-handed medium is incidented continuously, we can say that it looks as if the phase is propagating in the injection and opposite directions.

When discussing propagation of electromagnetic wave, it is not necessary to consider the dielectric constant and magnetic permeability individually; the refractive index is more commonly considered. To satisfy the law of causality, the refractive index of left-handed media must be negative[5] since left-handed media and negative refractive index are synonymous. An optical signal (electromagnetic wave) incidented from air into left-handed media is refracted in a quit different form from normal media, as shown in Figure 3(c). Since design of electromagnetic wave propagation is nothing more than design of the refractive index distribution, the use of left-handed media, which have very different characteristics from those of a natural media, enables a variety of propagation designs.



(a) Right-handed (b) Left-handed (c) Negative Refraction

Figure 3 Planar Electromagnetic Wave, Propagation Direction and Negative Index

3.2 Ideal Left-Handed Transmission Line Model

For simplicity, the following considers a one-dimensional (1D) medium, or in other words, the transmission line. It is not difficult to expand to two-dimensional (2D) surfaces using the same considerations.

As shown in Figure 4(a), a normal right-handed transmission line can be formulated by taking the limit of $\Delta z \to 0$ for a model in which a unit circuit consisted of an inductor and capacitor are connected as a cascade with a period of extremely small interval Δz. First, assuming Z and Y as the series impedance and parallel admittance per unit length, respectively, if the unit circuit input voltage and current are $V(z)$ and $I(z)$, respectively. Then, $\Delta V(z) = -(Z\,\Delta z)\,I(z)$ and $\Delta I(z) = -(Y\,\Delta z)\,V(z)$, we obtain

$$\frac{dV}{dz} = -Z\,I, \quad \frac{dI}{dz} = -Y\,V \tag{1}$$

for the limit $\Delta z \to 0$. In particular if Z and Y are lossless, we obtain,

$$\frac{dV}{dz} = -j\omega L\,I, \quad \frac{dI}{dz} = -\,j\omega C\,V \tag{2}$$

where, L and C are the reactance and capacitance per unit length (in F/m and H/m units).

On the other hand, in general media, the planar electromagnetic wave polarized to x-direction propagating toward z-direction is expressed by,

$$\frac{dE_x}{dz} = -j\omega\mu\,H_y\,, \quad \frac{dH_y}{dz} = -\,j\omega\varepsilon\,E_x\,. \tag{3}$$

Considering Eq. (1) and Eq. (3) where $E \propto V, and\ H \propto I$, we obtain the next analogys,

$$Z \Leftrightarrow j\omega\mu\,, \quad Y \Leftrightarrow j\omega\varepsilon\,. \tag{4}$$

In particular, the media are ideally lossless, we obtain the correspondence,

$$L \Leftrightarrow \mu\,, \quad C \Leftrightarrow \varepsilon\,. \tag{5}$$

Here, because the reactance of inductors is positive (inductive), and the reactance of capacitor is negative (capacitive), we can expect that the media dielectric constant and magnetic permeability are both negative, in other words, a left-handed medium is represented.

Assuming C' and L' as the capacitance and inductance per a reciprocal of unit length (in the units of F•m and H•m), respectively, we consider a line which is a infinit cascade of unit cells with a period of Δz shown in Figure 4(b), and the unit cell is composed of series capacitance $C'/\Delta z$ and parallel inductance $L'/\Delta z$. Since the impedance and admittance per unit length are $Z = 1/(j\omega C')$, $Y = 1/(j\omega L')$, by applying Eq. (4) we obtain,

$$\mu \Leftrightarrow -1/(\omega^2\,C')\;, \quad \varepsilon \Leftrightarrow -1/(\omega^2\,L')\,. \tag{6}$$

As expected, this model indicates a left-handed transmission line with negative permittivity and negative permeability.

The phase constant β (imaginary part of propagation constant $\gamma = \sqrt{ZY}$), phase velocity v_p, and group velocity v_g for the voltage wave propagating along the line are found as follows,

$$\beta = -\frac{1}{\omega\sqrt{L'C'}}\,, \qquad v_p = \frac{\omega}{\beta} = -\omega^2\sqrt{L'C'}\,, \quad v_g = \frac{d\omega}{d\beta} = \omega^2\sqrt{L'C'} \tag{7}$$

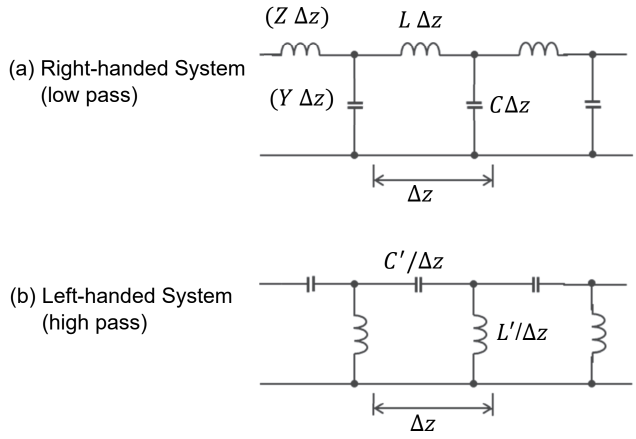


Figure 4 Right-Handed and Ideal Left-Handed Transmission Line Model

The phase velocity is negative and the reverse sign of group velocity. In other words, in a backward wave, the phase propagates in the opposite direction to the energy flow.

3.3 Composite Right/Left-Handed Transmission Line Model

The above-described left-handed transmission line model is easier to understand by analogy with the right-handed transmission line, but it is an ideal model, not a reality. The reason is that the group velocity exceeds the speed of light at high frequency because the phase delay in the small unit interval is not considered. Consequently, as shown in Figure 5, a more realistic model of composite right/left-handed transmission lines that includes the effect of the series inductance and parallel capacitance of each unit has been considered.[13), 14)] To distinguish the capacitor and inductor forming the right and left-handed systems, C and L, and C' and L' in Figure 4 are indicated as C_R and L_R, and C_L and L_L, respectively, in Figure 5. A part of the transmission line model in Figures 4 and 5 are nothing but a filter circuit combining the lumped elements. Figure 5 is a bandpass filter with the region near the lower end of the passband acting as a high pass filter and showing the characteristics of a left-handed transmission line. This can be understood as appearing to be a left-handed transmission line due to the capacitive series impedance and inductive parallel admittance at low frequencies.

The composite right/left-handed transmission line model can not only be directly implemented as a lumped element, but can also be applied to distributed constant circuits such as microstrip lines and waveguide circuits in a specific frequency band, and is applicable to resonators, couplers, and antennas. In particular, the characteristics of composite right/left-handed systems with designed phase constants are being examined for application to antenna miniaturization and feeders for array antennas. For example, leaky-waveguide array antennas (slot-array antennas) generally use a right-handed waveguide as a feeder. As a result, phase delay always occurs in the propagation direction and the antenna can only radiate in a direction inclined to the propagation-path side rather than the broadside direction. However, using a composite right/left-handed system as a feeder, the antenna can radiate in the direction inclined to the opposite side of the transmission direction because the feeder becomes the left-handed line in low frequency region. On the other hand, it can radiate in the direction inclined to the transmission direction because the feeder becomes the left-handed line in high frequency region.

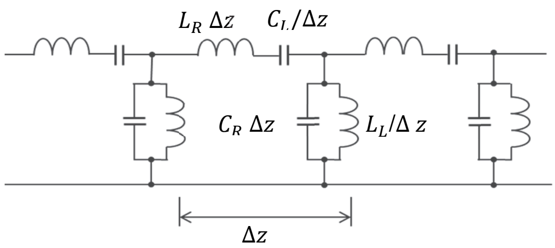


Figure 5 Left/Right-Handed Composite Transmission Line Model

Objects with composite right/left-handed transmission lines arranged in two dimensions are 2D metamaterials or meta-surfaces. The "mushroom" structure shown in Figure 6(a), is a known typical example. This structure is configured from the lower face of a dielectric substrate functioning as a ground plane, and an upper face of patches arranged as dense rectangles or hexagons connected to the ground plane using conductor via holes. Since the gaps between adjacent patches form series capacitance, the structure can be regarded as an LC resonator as shown in Figure 6(b). In addition, it can also be understood as extending the composite right/left-handed transmission lines in two dimensions as shown in Figure 6(c). The surface of the "mushroom" structure (substrate top surface) is known to function as an artificial magnetic wall in a specific band. And it becomes an electric wall if we consider the contactless surface as a short-circuit side without field tangent components. The magnetic wall has duality with electric wall, and forms a high impedance surface without tangential component of magnetic field. When a dipole antenna is bought close to a metal plate that is an electric wall, radiation from the dipole antenna is suppressed by the dipole induced in the opposite direction by the metal plate. Conversely, when a dipole antenna is brought close to an artificial magnetic wall, the radiation becomes stronger, then it is possible to construct a low profile antenna using these characteristics.

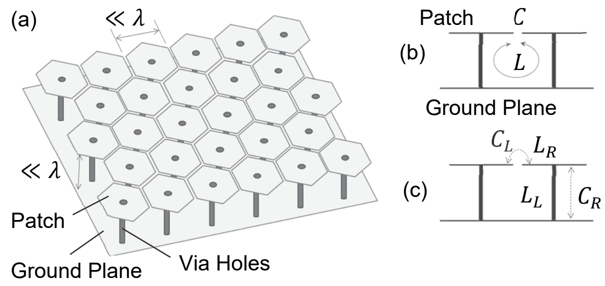


Figure 6 Mushroom Structure

4 Technology Trends

As described previously, in 2001 it was demonstrated that there are no naturally occurring negative index materials in the microwave region, and technologies for designing electromagnetic wave propagation using metamaterials started progressing. The propagation of electromagnetic waves in negative index media is very different from our everyday commonsense, and can increase the degrees of freedom in electromagnetic wave propagation design.

In fact, following the early research with deep interest in refraction and imaging, methods for designing new electromagnetic-wave propagation have been explored fully as listed in Table 1. For example, the list includes design of reflection properties for each polarization using metamaterials[15), 16)], as well as leaky-wave antennas and microwave resonators[17), 18)], non-reciprocal characteristics with the transmission line using ferrite. Additionally, research is continuing into the basic concept of coordinate conversion for achieving cloaking effects with materials that make things appear to be invisible.[19) to 22)] Recently, there are suggestions about space-time metamaterials in which the dielectric constant changes at about the same speed as the electromagnetic-wave frequency.[24) to 25)]

From the physics perspective, the fundamental theory of metamaterials remain within the electromagnetism framework, and no significant progress seems to have been made since the negative refractive index was pointed out. Incidentally, metamaterials with a periodic structure smaller than target electromagnetic wavelengths are often treated based on the effective media approximation, and expressions such as effective permeability have been use in this article. Since the unit cell of the structure is not negligibly small relative to the wavelength, the spatial homogenization method is not appropriate for obtaining the macroscopic permittivity and permeability of metamaterials, and it is necessary to base it on the averaging of the fields of each unit cell.[23)]

Metamaterials have properties that do not exist in nature and although they offer high degrees of freedom for designing electromagnetic-wave propagation, it is extremely difficult to fabricate 3D high-quality, large, low-loss media. In the circumstances of this challenging background for 3D metamaterials, recent attention has focused on designing electromagnetic-wave propagation paths using meta-surfaces with a 2D periodic structure smaller than the target electromagnetic wavelength.[26) to 29)] Since the thickness of meta-surfaces can be ignored, they have relatively low loss. They are easily mass-produced using common photolithographic methods and can be integrated on the same large board with semiconductor devices and circuits. The effective permitivity and effective permeability used to analyze metamaterials are not useful for meta-surfaces without thickness, and analysis of meta-surfaces is focused on understanding dispersion properties. When dealing with non-periodic structures, indices such as reflectance, spatial distribution of permeability, or surface impedance, etc., are used. Although the previously described “mushroom” structure is a typical meta-surface configuration for the microwave region, deep investigation is progressing into other applications including the optical region. For example, there are research reports on thin-lens antennas with polarization properties designed for azimuth angles[30)], wavelength boards for the microwave region using multi-refractive-index meta-surfaces[31)], polarization-wave switches using two-layer, chiral-metamaterial resonators[32)], one-wavelength-thick optical lenses with a semi-periodic structure[33)], and thin-optics holograms.[34)] Moreover, there are also proposals for digital meta-surfaces with the arrangement of unit elements linked to digital codes[35), 36)], and plasmonic meta-surfaces offering a quality similar to a metal-surface plasmon polariton.[37), 38)] Additionally, appropriate design of the surface impedance distribution is being proposed for meta-surfaces to induce surface currents distributed according to the injection wave. Using this Huygens meta-surface could achieve a fully refractive meta-surface refracting all incident power as an ideal medium that is thinner than the wavelength; it may also be possible to implement fully reflective meta-surfaces that can reflect at any angle.[39), 40)] The future holds promise for new applications by implementing these various electromagnetic-wave propagation designs including new concepts using meta-surfaces.

Table 1 Recent Research into Electromagnectic Wave Propagation Design using Metamaterials

Structure	Contents	Reference
3D	Design of reflection properties for polarized waves	15, 16
	Cloaking, electromagnetic conversion	19 to 22
	Space-time metamaterial	24, 25
2D (metasurface)	Design of polarization properties for azimuth angle	30
	Birefringent elements (wave plates, polarization separators)	31
	Circular birefringent elements (polarization wave switching)	32
	Thin optical elements (lens, hologram)	33, 34
	Digital meta-surface	35, 36
	Plasmonic meta-surface	37, 38
	Huygens surface	39, 40
1D	Non-reciprocal left-hand paths	17, 18

5 Conclusions

This article outlines typical negative-index metamaterial media in the microwave-band region and explains models of composite right/left-handed transmission lines by comparison with electrical circuits. Although resonators, such as metal-ring designs using 3D negative-index media, have very interesting properties, their applications are limited due to large loss and because they are essentially narrowband. Since 2D meta-surfaces and 1D composite right/left-handed transmission lines are relatively immune to these limitations, they are being widely adopted for use as antenna feeders, and so on.

As described previously, left-handed transmission lines are implemented as composite right/left-handed transmission lines near the resonance frequency. When generating resonance, the magnetic energy accumulated per unit length is large in comparison to left-handed propagation and the loss per unit length is generally large. Consequently, loss becomes remarkable in the high-frequency region, limiting applicability in the microwave band. However, the artificial magnetic wall, etc., is useful, which left-handed surfaces are expected to fully exploit. When designing a measuring instrument for use in communications fields, these materials can be used to suppress unwanted frequency components generated internally by mixers. One possible useful application is as a package functioning as a filter itself to suppress unwanted electromagnetic coupling between transmission lines and module inputs/outputs.

As described in the previous paragraph, research into metamaterials is continuing across a wide variety of fields. It is supported by advances in nanofabrication technology, and the future looks bright for new applications combining metamaterials demonstrating unique properties.

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