Part I

Introduction

Chapter 1

Categorization of Natural Materials and Metamaterials

An electromagnetic material is categorized by its constitutional parameters, permittivity ε and permeability μ. A double-positive (DPS) material ($\varepsilon > 0$ and $\mu > 0$) is defined as a right-handed (RH) material. The phase constant of wave propagation within the RH material exhibits a positive value ($\beta > 0$). A double-negative (DNG) material ($\varepsilon < 0$ and $\mu < 0$) is defined as a left-handed (LH) material. The phase constant of wave propagation within the LH material exhibits a negative value ($\beta < 0$). Note that β within a mu-negative (MNG) material ($\varepsilon > 0$ and $\mu < 0$) and an epsilon-negative (ENG) material ($\varepsilon < 0$ and $\mu > 0$) is zero (i.e., evanescent).

A DPS material is a material found easily in nature and called a natural material, while a DNG, MNG, or ENG material is an artificial material and called a metamaterial (MTM) [1].

1.1 NATURAL AND METAMATERIAL ANTENNAS DISCUSSED IN THIS BOOK

Most antennas are made of natural materials. Antennas based on metamaterials are new, and some examples are found in Refs [1–3]. The categorization of natural and metamaterial antennas presented *in this book* is in reference to β, the propagation phase constant of the *current* flowing along a *fed* element.

Figure 1.1a shows a fed antenna where the out-going current from the feed point F toward the antenna element ends flows with a positive phase constant ($\beta > 0$). This means that the phase distribution takes a regressive form, that is, the phase is delayed from point F toward the antenna element ends. This type of antenna is categorized as a *natural* (NTR) *antenna*.

Figure 1.1b shows a fed antenna where the propagation phase constant of the out-going current can be either negative within a specific frequency band ($\beta < 0$) or zero at a nonzero frequency ($\beta = 0$). This type of antenna is categorized as a *metamaterial-based antenna* (simply referred to as a metamaterial antenna). The phase

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Low-Profile Natural and Metamaterial Antennas: Analysis Methods and Applications, First Edition.
Hisamatsu Nakano.

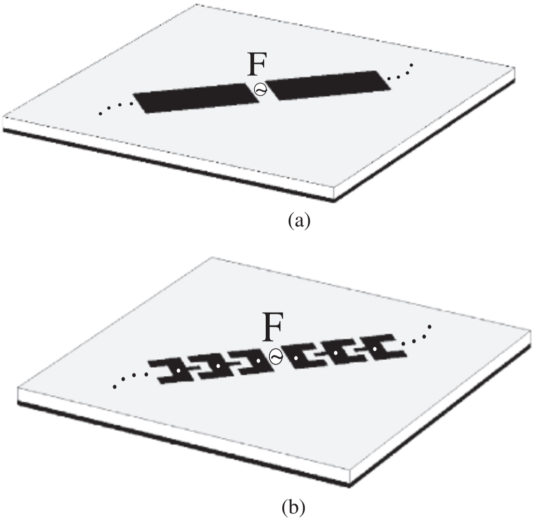


Figure 1.1 Antenna definition. (a) Natural antenna. The propagation phase constant is positive. (b) Metamaterial-based antenna (metamaterial antenna). The propagation phase constant is either negative within a specific frequency band or zero at a nonzero specific frequency.

distribution for $\beta < 0$ takes a progressive form from point F to the antenna element ends. A phase constant of zero ($\beta = 0$) means that the wavelength is infinitely long.

Exercise

Figure 1.2a shows a plane wave traveling within a lossless medium (permittivity ε and permeability μ) in the z-direction. Figure 1.2b shows a lossless transmission line characterized by distributed circuit parameters $[C'(F/m), L'(H/m), C'_Z(F \bullet m)$, and $L'_Y(H \bullet m)]$. Discuss the correspondence between the medium constitutional parameters (ε and μ) and the circuit parameters.

Answer Plane wave propagation within a lossless medium is specified by the following characteristic impedance Z_C and propagation constant γ:

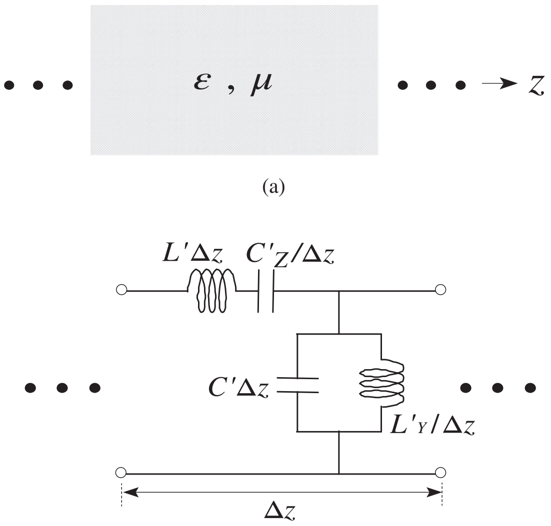
$$Z_C = \sqrt{\frac{\mu}{\epsilon}} \tag{1.1}$$

$$\gamma = j\omega\sqrt{\mu\epsilon} \tag{1.2}$$

The propagation of voltage and current in a lossless transmission line is specified by the following characteristic impedance Z_{MTM} and propagation constant γ_{MTM}:

$$Z_{MTM} = \sqrt{\frac{Z'}{Y'}} \tag{1.3}$$

$$\gamma_{MTM} = \sqrt{Z'\,Y'} \tag{1.4}$$



(a)

(b)

Figure 1.2 Equivalence. (a) Plane wave propagation within a lossless medium. (b) Lossless transmission line.

where

$$Z' = j\omega\left(L' - \frac{1}{\omega^2 C'_Z}\right) \equiv j\omega\,\mu_{TL} \tag{1.5}$$

$$Y' = j\omega\left(C' - \frac{1}{\omega^2 L'_Y}\right) \equiv j\omega\,\epsilon_{TL} \tag{1.6}$$

Then, Eqs. (1.3) and (1.4) are given by

$$Z_{MTM} = \sqrt{\frac{\mu_{TL}}{\epsilon_{TL}}} \tag{1.7}$$

$$\gamma_{MTM} = j\omega\sqrt{\mu_{TL}\epsilon_{TL}} \tag{1.8}$$

It is concluded that the medium constitutional parameters μ and ε correspond to the circuit parameters μ_{TL} and ϵ_{TL}, respectively,

$$\mu = \mu_{TL} = L' - \frac{1}{\omega^2 C'_Z} \tag{1.9}$$

$$\epsilon = \epsilon_{TL} = C' - \frac{1}{\omega^2 L'_Y} \tag{1.10}$$

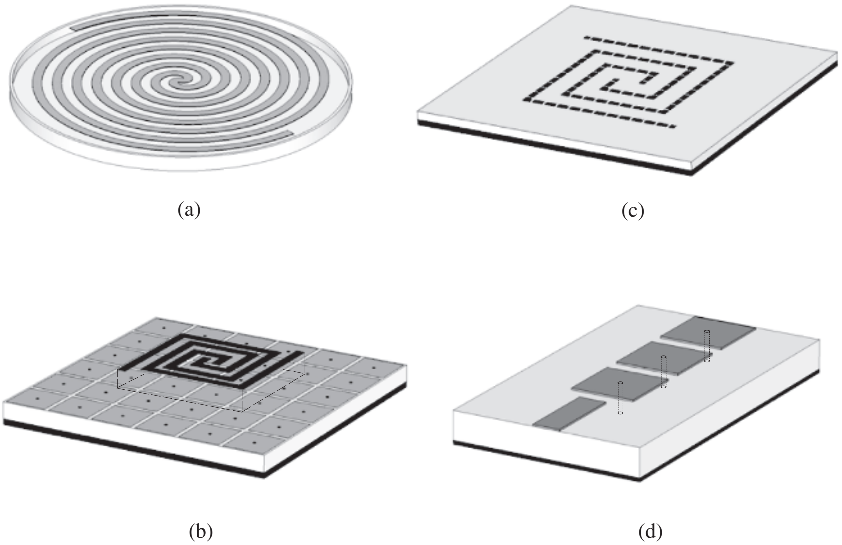
Note that μ_{TL} and ϵ_{TL} can both be negative across a specific frequency region. In such a situation (simultaneously $\mu_{TL} < 0$ and $\epsilon_{TL} < 0$), the transmission line in Fig. 1.2b has a negative phase constant of $\beta = -\omega\sqrt{|\epsilon_{TL}||\mu_{TL}|}$. $\blacksquare$

1.2 SOME ANTENNA EXAMPLES

The above-mentioned categorization is explained using some examples. Figure 1.3 shows spiral antennas, a spiral with a cavity (Fig. 1.3a) [4], and a spiral antenna above an electromagnetic band gap (EBG) reflector (Fig. 1.3b) [5]. These antennas are fed from their center terminals. The phase constant for the out-going current along each antenna arm is positive ($\beta > 0$). Hence, these antennas are categorized as natural antennas.

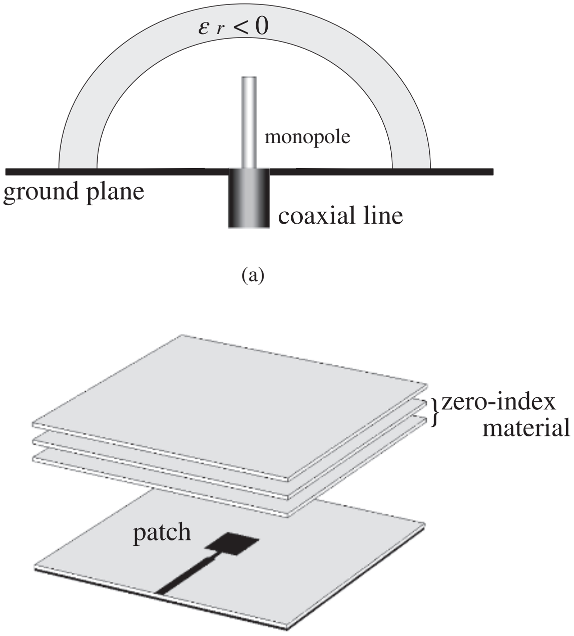
On the other hand, the current along the spiral arms in Fig. 1.3c shows a negative phase constant ($\beta < 0$) across a specific frequency band, as will be discussed in Chapter 22 [6]. Hence, this antenna is categorized as a metamaterial antenna. The antenna shown in Fig. 1.3d is designed using a zero phase constant ($\beta = 0$) at a nonzero frequency [7], and hence it is categorized as a metamaterial antenna.

Note that this book focuses on NTR and MTM antennas, as categorized above. Readers can find discussion on other MTM-related antennas [8–21], including an MTM-inspired antenna system composed of a fed element and an ENG or MNG metamaterial. The fed antennas used for the MTM-inspired antenna systems in Fig. 1.4a and b are, respectively, a natural monopole antenna and a natural patch antenna [the current of each antenna has a positive phase constant ($\beta > 0$)]. The effects of each MTM on the antenna system performance are discussed in Refs 20 and 21.


(a) (c)

(b) (d)

Figure 1.3 (a) Spiral antenna with a cavity. (Reproduced from Ref. [4] with permission from IET.) (b) Spiral antenna above an EBG reflector. (Reproduced from Ref. [5] with permission from IEEE.) (c) Metamaterial spiral (Metaspiral) antenna. (Reproduced from Ref. [6] with permission from IEEE.) (d) Zeroth-order resonance antenna. (Reproduced from Ref. [7] with permission from IEEE.)



(a)

(b)

Figure 1.4 MTM-inspired antenna systems. (a) Monopole surrounded by an ENG shell. (Reproduced from Ref. [20] with permission from IEEE.) (b) Patch with MTM layers. (Reproduced from Ref. [21] with permission from IEEE.)

Exercise

Figure 1.5 shows a situation where a plane wave illuminates a slab of thickness B, effective relative permittivity ε_r, and effective relative permeability μ_r. The phase constant within the slab is given by $\beta = k_0 \sqrt{\mu_r \epsilon_r}$, where $k_0 = \omega/c$ is the phase constant (real number) in free space, with ω and c being the angular frequency and the velocity of light, respectively. Express the wave impedance within the slab, using the scattering parameters S_{11} and S_{21} [22].

Answer Using a signal flow chart [23], the scattering parameters for a finite thickness slab are written as

$$S_{11} = \frac{(1-\varsigma^2)\Gamma}{1-\Gamma^2\varsigma^2} \tag{1.11}$$

$$S_{21} = \frac{(1+\Gamma)(1-\Gamma)\varsigma}{1-\Gamma^2\varsigma^2} = \frac{(1-\Gamma^2)\varsigma}{1-\Gamma^2\varsigma^2} \tag{1.12}$$

where

$$\Gamma = \frac{z-1}{z+1} \tag{1.13}$$

$$\begin{aligned} \varsigma &= \mathrm{e}^{-j\omega \frac{1}{c}\sqrt{\mu_r \epsilon_r} B} \\ &= \mathrm{e}^{-jk_0 nB} \end{aligned} \tag{1.14}$$

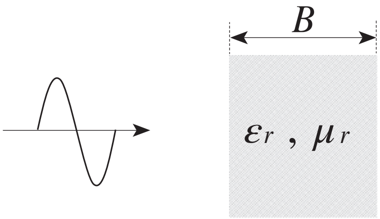


Figure 1.5 A plane wave illuminating a slab of effective relative permittivity ε_r, effective relative permeability μ_r, and thickness B.

Note that z in Eq. (1.13) is the wave impedance within the slab normalized to the free-space wave impedance Z_0, and n in Eq. (1.14) is the refractive index.

From Eqs. (1.11) and (1.12), Γ is expressed as

$$\Gamma = \xi \pm \sqrt{\xi^2 - 1}, \tag{1.15}$$

where

$$\xi = \frac{1 - (S_{21}^2 - S_{11}^2)}{2S_{11}} \tag{1.16}$$

The normalized wave impedance z in Eq. (1.13) is calculated using Γ from Eq. (1.15):

$$z = \pm\sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \tag{1.17}$$

where the sign should be chosen so that the real part of z is

$$\mathrm{Re}[z] \geq 0. \tag{1.18}$$

■

REFERENCES

1. N. Engahta and R. Ziolkowski, *Metamaterials*, NJ: Wiley, 2006.
2. C. Caloz and T. Itoh, *Electromagnetic metamaterials*, NJ: Wiley, 2006.
3. G. Eleftheriades and K. Balmain, *Negative-refraction metamaterials: fundamental principles and applications*, NJ: Wiely, 2005.
4. H. Nakano, S. Sasaki, H. Oyanagi, and J. Yamauchi, Cavity-backed Archimedean spiral antenna with strip absorber. *IET Microw. Antennas Propag.*, vol. 2, no. 7, pp. 725–730, 2008.
5. H. Nakano, K. Hitosugi, N. Tatsuzawa, D. Togashi, H. Mimaki, and J. Yamauchi, 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. Antennas Propag.*, vol. 53, no. 1, pp. 191–199, 2005.
6. H. Nakano, J. Miyake, M. Oyama, and J. Yamauchi, Metamaterial spiral antenna. *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 1555–1558, 2011.

7. A. Lai, M. K. H. Leong, and T. Itoh, Infinite wavelength resonant antennas with monopolar radiation pattern based on periodic structures. *IEEE Trans. Antennas Propag.*, vol. 55, no. 3, pp. 868–876, 2007.
8. M. A. Antoniades and G. V. Eleftheriades, A folded-monopole model for electrically small NRI-TL metamaterial antennas. *IEEE Antennas Wirel. Propag. Lett.*, vol. 7, pp. 425–428, 2008.
9. M. A. Antoniades and G. V. Eleftheriades, A broadband dual-mode monopole antenna using NRI-TL metamaterial loading. *IEEE Antennas Wirel. Propag. Lett.*, vol. 8, pp. 258–261, 2009.
10. F. Qureshi, M. A. Antoniades, and G. V. Eleftheriades, Compact and low-profile metamaterial ring antenna with vertical polarization. *IEEE Antennas Wirel. Propag. Lett.*, vol. 4, pp. 333–336, 2005.
11. J. Zhu, M. A. Antoniades, and G. V. Eleftheriades, A compact tri-band monopole antenna with single-cell metamaterial loading, *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1031–1038, 2010.
12. J.-H. Park, Y.-H. Ryu, J. G. Lee, and J. H. Lee, Epsilon negative zeroth-order resonator antenna. *IEEE Trans. Antennas Propag.*, vol. 55, pp. 3710–3712, 2007.
13. W. Liu, Z. N. Chen, and X. Qing, Metamaterial-based low-profile broadband mushroom antenna. *IEEE Trans. Antennas Propag.*, vol. 62, no. 3, pp. 1165–1172, 2014.
14. Nasimuddin, Z. N. Chen, and X. Qing, Substrate integrated metamaterial-based leak-wave antenna with improved boresight radiation bandwidth. *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3451–3457, 2013.
15. M. Sun, Z. N. Chen, and X. Qing, Gain enhancement of 60-GHz antipodal tapered slot antenna using zero-index metamaterial. *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1741–1746, 2013.
16. Nasimuddin, Z. N. Chen, and X. Qing, Multilayered composite right/left-handed leaky-wave antenna with consistent gain. *IEEE Trans. Antennas Propag.*, vol. 60, no. 11, pp. 5056–5062, 2012.
17. P. Jin and R. W. Ziolkowski, Metamaterial-inspired, electrically small, Huygens sources. *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 501–505, 2010b.
18. P. Jin and R. W. Ziolkowski, Multi-frequency, linear and circular polarized, metamaterial-inspired near-field resonant parasitic antennas. *IEEE Trans. Antennas Propag.*, vol. 59, pp. 1446–1459, 2011.
19. N. Zhu and R. W. Ziolkowski, Active metamaterial-inspired broad bandwidth, efficient, electrically small antennas. *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 1582–1585, 2011.
20. R. W. Ziolkowski and A. Erentok, Metamaterial-based efficient electrically small antennas. *IEEE Trans. Antennas Propag.*, vol. 54, no. 7, pp. 2113–2130, 2006.
21. D. Li, Z. Szabó, X. Qing, Er.-P. Li, and Z. N. Chen, A high gain antenna with an optimized metamaterial inspired superstrate. *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 6018–6023, 2012.
22. A. M. Nicolson and G. F. Ross, Measurement of the intrinsic properties of materials by time-domain techniques. *IEEE Trans. Instrum. Meas.*, vol. IM-19, no. 4, pp. 377–382, 1970.
23. D. Pozar, *Microwave engineering*, second edition, Wily, NY, 1998.