frontiers | Frontiers in Antennas and Propagation

TYPE Grand Challenge
PUBLISHED 11 November 2022
DOI 10.3389/fanpr.2022.1032205

EDITED AND REVIEWED BY
Francisco Falcone,
Public University of Navarre, Spain

*CORRESPONDENCE
Bal Virdee,
b.virdee@londonmet.ac.uk

SPECIALTY SECTION
This article was submitted to
Metamaterial Antennas,
a section of the journal
Frontiers in Antennas and Propagation

RECEIVED 30 August 2022
ACCEPTED 25 October 2022
PUBLISHED 11 November 2022

CITATION
Virdee B (2022), Grand challenges in
metamaterial antennas.
Front. Antennas Propag. 1:1032205.
doi: 10.3389/fanpr.2022.1032205

Grand challenges in metamaterial antennas

Bal Virdee*

Center for Communications Technology, School of Computing & Digital Media, London Metropolitan University, London, United Kingdom

KEYWORDS

metamaterial antenna, electrically small antennas, multiband antenna, antenna lens, antenna polarization, wireless power transfer

Introduction

Metamaterials are artificial synthetic composite materials that are engineered to exhibit a specific electromagnetic response that is not found in natural materials (Wikipedia, 1997). In fact, periodic structures are commonly used in the realization of metamaterials to display a negative permittivity or permeability, and zero refractive index (Lapine and Tretyakov, 2007; Sihvola, 2007). These characteristic properties of metamaterials are dictated by the arrangement of their constituent parts. The components constituting metamaterials are commonly referred to as meta-atoms or metamolecules, and can be periodically arranged in one, two, or three dimensions. The electromagnetic coupling of these components makes it possible to elicit and modify metamaterial properties.

The original concepts of negative refraction and double negative materials were first coined by Mandelstam and Veselage in 1945 (Mandelstam, 1945) and 1967 (Veselago, 1968), respectively. The feasibility of negative refraction was first experimentally verified by Smith and Pendry in 2000 (Pendry et al., 1999; Shelby et al., 2001). Although great progress has been made in this field in the new century (Padilla et al., 2006; Lapine and Tretyakov, 2007; Sihvola, 2007; Zheludev, 2010; Caloz, 2011; McPhedran et al., 2011; Zheludev and Kivshar, 2012), a unique, clear and accurate definition of the general concept "metamaterial" is still a matter of debate. However, there are several generally accepted features for a metamaterial, the most important of them all is that it is required that the dimensions of the unit-cells, and thus the periodicity of the metamaterial, are much smaller than the operating wavelength. This ensures that one obtains a quasi-homogeneous material (Lapine and Tretyakov, 2007; Sihvola, 2007). This is a clear difference with other periodic structures, e.g., photo crystals, scattering arrays, electromagnetic bandgap topologies, frequency selective surfaces etc.

Antennas are one of the pivotal components that makes wireless communications possible. The function of antennas is to interface the radio system with the external environment. Wireless communication systems require antennas at the transmitter and receiver to operate properly. The concept of metamaterials has been widely applied in the design of microwave, millimetre-wave and terahertz devices and antennas. With the fast development of flexible portable devices such as mobile phones, laptops, wearable devices, etc., antennas with different tuneable functions, based on variable structures, are in demand for next generation of wireless communication systems.

The application of metamaterials over the past decade has achieved great successes in the fields of both science and engineering. Variable metamaterials have been designed from radio frequencies up to optical frequencies, and different functions have been realized, e.g., negative refractive index (NRI), anisotropy and bianisotropy (Lapine and Tretyakov, 2007; Sihvola, 2007). As an interdisciplinary topic, metamaterials can be classified into different categories based on different criteria. From an operating frequency point of view, they can be classified as microwave metamaterials, terahertz metamaterials, and photonic metamaterials. From a spatial arrangement point of view, there are 1D metamaterials, 2D metamaterials, and 3D metamaterials. From a material point of view, there are metallic and dielectric metamaterials.

One of the most important applications of metamaterials is antenna design. Due to the unusual properties of metamaterials, we can achieve antennas with novel characteristics which cannot be realized with traditional materials. In subsequent sections, several types of metamaterial antennas will be briefly reviewed.

Electrically small antennas

Electrically small antennas (ESA) are highly desired for wireless applications as they can be easily integrated with devices without compromising the system form factor. The performance of antennas in terms of bandwidth, gain etc. is extremely critical and is governed by fundamental limitations in size, i.e., Chu's limit (Chu, 1948). Although modern integrated circuit technology can miniaturize electronic circuits to a very small size however, in traditional designs, the performance of the antenna is related to its physical size. The antenna usually has dimensions in the order of the operating wavelength. Consequently, this sets boundaries for the size of the whole wireless system (Garg et al., 2001; Wong, 2002; Kumar and Ray, 2003; Balanis, 2012). This issue makes metamaterials a hot topic for research in the development of electrically small antennas. This is an opportunity for using a zero refractive index metamaterial (ZIM) medium as its operating wavelength is infinite at the design frequency. Since the wavenumber in ZIM antennas is zero, in theory, the physical size of such antennas can be made independent of its operating frequency (Sanada et al., 2003; Lai et al., 2004; Sanada et al., 2004; Yan and Vandenbosch, 2014).

Multiband antennas

Mobile communication systems need to support multiple communication standards, e.g., 5G, Bluetooth, WiFi, NFC etc. To save space it is desirable to have a single antenna that can simultaneously accommodate these standards. Multiband antennas are normally designed with different resonant structures. The disadvantage of this technique is the large size of the resulting antenna, which is dictated by the lowest operating frequency (Herraiz-Martinez et al., 2008; Wang et al., 2010). Because metamaterial structures can support negative and positive modes along with a zeroth-order mode, this property can be exploited to realize a singular antenna that operates over multiple bands and is miniature to boot.

Antenna lenses and polarizers

Directivity and gain of an antenna can be improved with dielectric lenses. The only drawback of this technique is the exorbitant cost of the 3D lens. Moreover, the location of the lens needs to be carefully selected in relation with the phase center of the antenna. The high cost of the lens can be offset by using a 2D lens made from metamaterial, which can be easily integrated with the planar antenna structure to reduce the profile and size of the antenna system (Wu et al., 2007; Grbic et al., 2011).

Polarizers are universal components employed in diverse application including antennas, imaging, display and microscopy. A polarizer based on a chiral medium are used to transform a linearly polarized wave into a circularly polarized wave, and to date various polarization convertors have been proposed (Hosseininnejad et al., 2012; Zhu et al., 2013; Zhu et al., 2014). In wireless communications transmitter-receiver alignment is imperative when using linearly polarized electromagnetic waves. However, in reality the polarization of the propagating signal will experience change due to reflections and Faraday rotation by the ionosphere. Non-alignment in polarization will result in signal fading. This issue can be eliminated by utilizing circularly polarized electromagnetic waves (Kraus and Marhefka, 2003).

Conventional methods to fabricate polarization convertors is to use optical gratings, anisotropic medias, the Brewester and Faraday effects (Wu et al., 2013; Kim et al., 2012a; Almpanis et al., 2017). Polarization convertors developed using metasurfaces have the advantage of scalable geometries when compared to the conventional polarization convertors, and there is scope for further improvement (Hao et al., 2007; Kaouach et al., 2011; Wang et al., 2013; Tamayama et al., 2014; Li et al., 2015).

Other types of antennas based on metamaterials

Other examples of radiating structures based on metamaterials include leaky wave antennas (Caloz and Itoh, 2004; Nguyen et al., 2007; Caloz et al., 2008; Losito et al., 2011), magnetodielectric microstrip antennas (Ikonen et al., 2006; Mosallaei and Sarabandi, 2007), ultra-wideband (UWB) antennas with notched bands (Zhang et al., 2008; Kim et al., 2012b) etc. All these designs exhibit better performance than the corresponding conventional designs.

Future challenges

Electrically small antennas

Dimensions of electrically small antennas are considerably small in relation to the operating wavelength. However, the design of ESA is challenging due to their limitations, which requires compromises between antenna size and performance in terms of bandwidth and radiation efficiency. Although metamaterials have proved to be effective in reducing the size of the radiating elements by enabling zeroth-order modes, the main challenges remain unchanged. For instance, the narrowband nature of metamaterials directly affects the bandwidth of the small meta resonator antennas. To date most of the designs are focused exclusively on reducing the size of the antenna by leveraging the subwavelength resonance of metamaterial cells, however the overall antenna performance is suboptimum. In particular, the interaction between the metamaterial cell and the rest of the antenna is not considered even though this interaction is vital for determining the antenna performance.

Although ESA designs based on metamaterials are relatively straightforward, but accomplishing an overall excellent performance from them will require considerations of other factors such as feeding mechanism, metamaterial structure, position of the unit cells, antenna housing, etc. Moreover, theoretical formulations for such antennas are important to provide an insight of the key characterising parameters as well as for providing design guidelines. It is evident from recent literature that field is not mature yet and although there are some great examples of metamaterial antennas, the scientific insight into the working principles is limited and the designs mainly rely on electromagnetic simulations. To expedite the design of ESA for desirable performance characteristics what is needed is formulation of accurate theory behind metamaterial inspired antennas. More specifically, we need techniques for increasing the bandwidth and improving the radiation efficiency of ESAs. Small, energy efficient and wideband antennas will be vital components for next generation of wireless communication systems.

Antenna gain

The gain of an antenna is affected by its size and aperture efficiency. Recent techniques proposed to improve gain include near-zero refractive index (NZRI) superstrates and artificial magnetic conductor (AMC) surfaces. This is because NZRI superstrates can focus the electromagnetic energy, and AMC acts like as reflecting surface. Metamaterial inspired gradient-index (GRIN) lenses have also been shown to enhance gain and this is over a wide bandwidth (Thippeswamy et al., 2021). The improvement in gain of these techniques is mainly due to the increase in the aperture size. Moreover, NZRI and AMC surfaces are easier to fabricate and cheaper than metallic reflectors that require extreme surface smoothness in higher frequencies.

Gain enhancement techniques based on NRZI and AMC superstrates have only been applied to fixed-beam antennas because these superstrates focus the radiation energy at a specific direction. However, investigation remains to be done of integrating superstrates with beam steerable antennas. The viability of concurrent gain enhancement and beam steering will truly be possible when metamaterials can be dynamically configured so that they adapt in real time to the changes in the transmit-receive environment.

GRIN lens integrated beam steerable antennas achieve beam steering by either mechanical means or by switching between radiating elements positioned at different orientation. This is a cumbersome approach and hence there is a need for a dynamic solution which can be electronically controlled and agile. Unfortunately, GRIN lenses are incompatible for various low profile various applications.

The overall telecommunications industry accounts for about 1.4% of carbon emissions worldwide. By comparison, the aviation industry generates 2% of all global carbon emissions. Clearly transformational change is required in wireless communications towards achieving net-zero carbon emissions. Beamforming is a key technology in 5G and beyond systems that reduces carbon emissions by focusing the wireless signal towards a specific receiving device, rather than transmitting the signal in all directions. The direct connection results in a faster, high-quality, and more reliable communications connection than it would be without beamforming. To achieve further improvements in the system performance and thereby reduce greenhouse gases requires increase in the beam gain and radiation efficiency of beam steerable arrays. This entails further research on adaptive NRZI and AMC metasurfaces and low-profile metamaterial GRIN lenses.

Antenna isolation

In 5G wireless systems the use of massive multiple-input multiple-out (MIMO) is essential to increase the cell capacity and downloading data rates of user equipment. This is achieved with multiple antennas that co-exist on the same platform and operate on the same frequency bands. However, the performance of massive MIMO can be undermined by the mutual coupling interaction between the radiating elements constituting the antenna array. The suppression of unwanted coupling in arrays which are based on metamaterial decoupling techniques have been demonstrated to be quite effective (Zhang et al., 2019). This is achieved by inserting the metamaterial decoupler between the adjacent radiating elements. The benefit of using metamaterial is that it provides a low-profile solution and, in most cases, has no impact on the size of the array. Space permitting it can in some cases be retrofitted to existing antenna arrays.

The main disadvantage of metamaterial inspired decoupling techniques reported to date in literature is their narrowband limitation. For existing and next generation of wireless communication systems to operate across multiple bands makes the narrowband metamaterial decoupling an ineffective solution. Mutual coupling isolation of -20 dB is acceptable in MIMO systems. Similarly in the case of CW or FMCW radar systems the performance is dependent on the isolation between the transmitter and receiver. In the case of radars, isolation of better than 100 dB is required for interference immunity. Clearly decoupling over a wideband is a challenge and a low-profile metamaterial decoupling is highly preferred in place of using a conductive shield. Investigation is therefore required in the development of novel metamaterial techniques that can provide isolation over a wideband for application in multiband wireless systems.

Frequency variation

A critical parameter which can affect an antenna’s performance is frequency. An antenna is designed at a specific frequency and therefore its performance is effective over a range of frequencies centered on its resonant frequency. However, because the antenna’s other properties (e.g., radiation pattern and impedance) change with frequency, its resonant frequency may just be close to the center frequency of these other properties. Therefore, a design technique based on metamaterial needs to be investigated that minimizes such frequency variations.

Wireless power transfer

The need for wireless power transfer (WPT) for electric vehicles (EV) is growing in demand (Zhang et al., 2018). However, currently there are technical bottlenecks for current WPT technologies, such as the low-energy efficiency, short transmission range and electromagnetic exposure, etc. The metamaterials exhibit great potentials to concentrate and enhance the magnetic flux density of the electromagnetic field by means of its left-handed characteristics. A brand-new research field is emerging by combining WPT and metamaterial technologies to enhance the transmission of wireless power.

Conclusion

Future wireless technologies necessitate the development of next generation subsystems of antennas that are highly efficient and capable of simultaneously supporting multiple functions for the transmission and reception of RF signals over a wide frequency band. Reduction in antenna size has become a critical factor in the miniaturization of wireless communication systems. The challenge for researchers in academia and industry is to develop innovative solutions by exploiting the novel characteristics exhibited by 2D and 3D metamaterials. The importance of antennas and in particular antennas that exploit the unique properties of metamaterials is evident in literature. Discussed here were the need for electrically small antennas, antenna gain, and isolation enhancement based on metamaterial principles. It is also noted that wireless power transfer technologies incorporating the metamaterial can offer an enhanced transmission performance. With increasing application of wireless charging technologies for EVs, the study on the metamaterial based WPT is undoubtedly needed. It is evident that metamaterial inspired antennas offer exciting new opportunities for existing and future wireless communications and radar systems. Novel properties of metamaterials have made possible the establishment of new design methodologies that were unavailable previously. However, the review of recent literature shows that many design challenges are yet to be addressed. The challenges discussed here should inspire researchers to make their mark by developing innovative metamaterial antennas for a wide range of applications.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

Publisher’s note

References

Almpanis, E., Pantazopoulos, P. A., Papanikolaou, N., Yannopapas, V., and Stefanou, N. (2017). A birefringent etalon enhances the Faraday rotation of thin magneto-optical films. *J. Opt.* 19 (7), 075102. doi:10.1088/2040-8986/aa7420

Balanis, C. A. (2012). *Antenna theory: Analysis and design*. Hoboken, New Jersey: John Wiley & Sons.

Caloz, C., and Itoh, T. (2004). Array factor approach of leaky-wave antennas and application to 1-D 2-D composite right left-handed (CRLH) structures. *IEEE Microw. Wirel. Components Lett.* 14 (6), 274–276. doi:10.1109/lmwc.2004.828009

Caloz, C., Itoh, T., and Rennings, A. (2008). CRLH metamaterial leaky-wave and resonant antennas. *IEEE Antennas Propag. Mag.* 50 (5), 25–39. doi:10.1109/map.2008.4674709

Caloz, C. (2011). *Next-generation metamaterials for unprecedented microwave systems," TELSIKS, Serbia*. Serbia: Nis, 3–12.

Chu, L. J. (1948). Physical limitations of omnidirectional antennas. *J. Appl. Phys.* 19, 1163–1175. doi:10.1063/1.1715038

Garg, R., Bhartia, P., Bahl, I., and Ittipiboon, A. (2001). *Microstrip antenna design handbook*. London, United Kingdom: Artech House.

Grbic, A., Merlin, R., Thomas, E. M., and Imani, M. F. (2011). Near-field plates metamaterial surfaces arrays for subwavelength focusing and probing. *Proc. IEEE* 99 (10), 1806–1815, Oct. doi:10.1109/jproc.2011.2106191

Hao, J., Yuan, Y., Ran, L., Jiang, T., Kong, J. A., Chan, C. T., et al. (2007). Manipulating electromagnetic wave polarizations by anisotropic metamaterials. *Phys. Rev. Lett.* 99 (6), 063908. doi:10.1103/physrevlett.99.063908

Herraiz-Martinez, F. J., Gonzalez-Posadas, V., Garcia-Munoz, L. E., and Segovia-Vargas, D. (2008). Multifrequency and dual-mode patch antennas partially filled with left-handed structures. *IEEE Trans. Antennas Propag.* 56 (8), 2527–2539. doi:10.1109/tap.2008.927518

Hosseininnejad, S. E., Komjani, N., Zarifi, D., and Rajabi, M. (2012). Directivity enhancement of circularly polarized microstrip antennas by chiral metamaterial covers. *IEICE Electron. Express* 9 (2), 117–121. doi:10.1587/elex.9.117

Ikonen, P. M. T., Maslovski, S. I., Simovski, C. R., and Tretyakov, S. (2006). On artificial magnetodielectric loading for improving the impedance bandwidth properties of microstrip antennas. *IEEE Trans. Antennas Propag.* 54 (6), 1654–1662. doi:10.1109/tap.2006.875912

Kaouach, H., Dussopt, L., Lanteri, J., Koleck, T., and Sauleau, R. (2011). Wideband low-loss linear and circular polarization transmit-arrays in V-band. *IEEE Trans. Antennas Propag.* 59 (7), 2513–2523. doi:10.1109/tap.2011.2152331

Kim, J., Komanduri, R. K., Lawler, K. F., Kekas, D. J., and Escuti, M. J. (2012). Efficient and monolithic polarization conversion system based on a polarization grating. *Appl. Opt.* 51 (20), 4852–4857. doi:10.1364/ao.51.004852

Kim, J. Y., Oh, B. C., Kim, N., and Lee, S. (2012). Triple band-notched UWB antenna based on complementary meander line SRR. *Electron. Lett.* 48 (15), 896–897. doi:10.1049/el.2012.1921

Kraus, J. D., and Marhefka, R. J. (2003). *Antennas for all applications*. 3rd ed. New York City: McGraw-Hill.

Kumar, G., and Ray, K. P. (2003). *Broadband microstrip antennas*. London, United Kingdom: Artech House.

Lai, A., Caloz, C., and Itoh, T. (2004). Composite right/left-handed transmission line metamaterials. *IEEE Microw. Mag.* 5 (3), 34–50. doi:10.1109/mmw.2004.1337766

Lapine, M., and Tretyakov, S. (2007). Contemporary notes on metamaterials. *IET Microwaves, Antennas Propag.* 1 (1), 3–11. doi:10.1049/iet-map:20050307

Li, Y., Zhang, J., Qu, S., Wang, J., Zheng, L., Pang, Y., et al. (2015). Achieving wide-band linear-to-circular polarization conversion using ultra-thin bi-layered metasurfaces. *J. Appl. Phys.* 117, 044501. doi:10.1063/1.4906220

Losito, O., Gallo, M., Dimiccoli, V., Barletta, D., and Bozzetti, M. (2011). "A tapered design of a CRLH-TL leaky wave antenna," in Proceedings of the 5th European Conference on IEEE, Amsterdam, Netherlands 357–360.

Mandelstam, J. B. (1945). Group velocity in crystal lattice. *Zh. Eksp. Teor. Fiz.* 15 (9), 475–478.

McPhedran, R. C., Shadrivov, I. V., Kuhlmey, B. T., and Kivshar, Y. S. (2011). Metamaterials and metaoptics. *NPG Asia Mater.* 3 (11), 100–108. doi:10.1038/asiamat.2011.146

Mosallaei, H., and Sarabandi, K. (2007). Design and modeling of patch antenna printed on magneto-dielectric embedded-circuit metasubstrate. *IEEE Trans. Antennas Propag.* 55 (1), 45–52. doi:10.1109/tap.2006.886566

Nguyen, H. V., Abielmona, S., Rennings, A., and Caloz, C. (2007). "Pencil-beam full-space scanning 2D CRLH leaky-wave antenna array IEEE Signals, Systems and Electronics," in Proceedings of the International Symposium on 2007, Nice, France. 139–142.

Padilla, W. J., Basov, D. N., and Smith, D. R. (2006). Negative refractive index metamaterials. *Mater. today* 9 (7), 28–35. doi:10.1016/s1369-7021(06)71573-5

Pendry, J. B., Holden, A. J., Robbins, D. J., and Stewart, W. (1999). Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Trans. Microw. Theory Tech.* 47, 2075–2084. doi:10.1109/22.798002

Sanada, A., Caloz, C., and Itoh, T. (2003). "Novel zeroth-order resonance in composite right/left-handed transmission line resonators,"in Proceedings of the. Asia-Pacific Microwave Conference, Seoul, Korea 1588–1591.

Sanada, A., Kimura, M., Awai, I., Itoh, T., and Caloz, C. (2004). "A planar zeroth-order resonator antenna using a left-handed transmission line,"in 34th European, IEEE Microwave Conference, Amsterdam 1341–1344.

Shelby, R. A., Smith, D. R., and Schultz, S. (2001). Experimental verification of a negative index of refraction. *Science* 292 (5514), 77–79. doi:10.1126/science.1058847

Sihvola, A. (2007). Metamaterials in electromagnetics. *Metamaterials* 1 (1), 2–11. doi:10.1016/j.metmat.2007.02.003

Tamayama, Y., Yasui, K., Nakanishi, T., and Kitano, M. (2014). A linear-to-circular polarization converter with half transmission and half reflection using a single-layered metamaterial. *Appl. Phys. Lett.* 105 (2), 021110. doi:10.1063/1.4890623

Thippeswamy, M. C, Kuchibhatla, S. A. R., and Rajagopal, P. (2021). Concentric shell gradient index metamaterials for focusing ultrasound in bulk media. *Ultrasonics* 114, 106424. doi:10.1016/j.ultras.2021.106424

Veselago, V. G. (1968). The electrodynamics of substances with simultaneously negative values of ϵ and μ. *Sov. Phys. Uspekhi* 10, 509–514. doi:10.1070/pu1968v010n04abeh003699

Wang, C., Hu, B.-J., and Zhang, X.-Y. (2010). Compact triband patch antenna with large scale of frequency ratio using CRLH-TL structures. *IEEE Antennas Wirel. Propag. Lett.* 9, 744–747. doi:10.1109/lawp.2010.2060711

Wang, L., Hu, H., Liu, K., Jiang, S., Zeng, W., and Gan, Q. (2013). Polarization management of terahertz extraordinary optical transmission through ultracompact L-shaped subwavelength patterns on metal films. *Plasmonics* 8 (2), 733–740. doi:10.1007/s11468-012-9464-z

Wikipedia (1997). Metamaterial. Available at: http://en.wikipedia.org/wiki/Metamaterial.

Wong, K. L. (2002). *Compact and broadband microstrip antennas*. Hoboken, New Jersey: Wiley.

Wu, Q., Pan, P., Meng, F. Y., Li, L. W., and Wu, J. (2007). A novel flat lens horn antenna designed based on zero refraction principle of metamaterials. *Appl. Phys. A* 87 (2), 151–156. doi:10.1007/s00339-006-3820-9

Wu, S., Zhang, Z., Zhang, Y., Zhang, K., Zhou, L., Zhang, X., et al. (2013). Enhanced rotation of the polarization of a light beam transmitted through a silver film with an array of PerforatedS-shaped holes. *Phys. Rev. Lett.* 110 (20), 207401. doi:10.1103/physrevlett.110.207401

Yan, S., and Vandenbosch, G. A. E. (2014). Zeroth-order resonant circular patch antenna based on periodic structures. *IET Microwaves, Antennas Propag.* 8 (15), 1432–1439. doi:10.1049/iet-map.2014.0134

Zhang, S., Chen, X., and Pedersen, G. F. (2019). Mutual coupling suppression with decoupling ground for massive MIMO antenna arrays. *IEEE Trans. Veh. Technol.* 68 (8), 7273–7282. doi:10.1109/tvt.2019.2923338

Zhang, Y., Hong, W., Yu, C., Kuai, Z. Q., Don, Y. D., and Zhou, J. Y. (2008). Planar ultrawideband antennas with multiple notched bands based on etched slots on the patch and or split ring resonators on the feed line. *IEEE Trans. Antennas Propag.* 56 (9), 3063–3068. doi:10.1109/tap.2008.928815

Zhang, Z., Zhang, B., Deng, B., Wei, X., and Wang, J. (2018). Opportunities and challenges of metamaterial-based wireless power transfer for electric vehicles. *Wirel. Power Transf.* 5, 9–19. doi:10.1017/wpt.2017.12

Zheludev, N. I., and Kivshar, Y. S. (2012). From metamaterials to metadevices. *Nat. Mater.* 11, 917–924. doi:10.1038/nmat3431

Zheludev, N. I. (2010). The road ahead for metamaterials. *Science* 328 (5978), 582–583. doi:10.1126/science.1186756

Zhu, H. L., Cheung, S. W., Chung, K. L., and Yuk, T. I. (2013). Linear-to-circular polarization conversion using metasurface. *IEEE Trans. Antennas Propag.* 61 (9), 4615–4623. doi:10.1109/tap.2013.2267712

Zhu, H. L., Cheung, S. W., Liu, X. H., and Yuk, T. I. (2014). Design of polarization reconfigurable antenna using metasurface. *IEEE Trans. Antennas Propag.* 62 (6), 2891–2898. doi:10.1109/tap.2014.2310209