Engineering 2015, 1(2): 179–184
DOI 10.15302/J-ENG-2015036

Research

Advanced Materials and Materials Genome—Review

Metamaterials: Reshape and Rethink

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ABSTRACT Metamaterials are composite materials whose material properties (acoustic, electrical, magnetic, or optical, etc.) are determined by their constitutive structural materials, especially the unit cells. The development of metamaterials continues to redefine the boundaries of materials science. In the field of electromagnetic research and beyond, these materials offer excellent design flexibility with their customized properties and their tunability under external stimuli. In this paper, we first provide a literature review of metamaterials with a focus on the technology and its evolution. We then discuss steps in the industrialization process and share our own experience.

KEYWORDS metamaterials, metasurface, smart structure, metadevices, industrialization

1 Introduction

A metamaterial is an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties (Figure 1). The advantage of metamaterials over their conventional counterparts comes from their designability. With their customized dielectric properties and tunable responses, metamaterials offer excellent flexibility in material design and bring a new perspective in understanding materials.

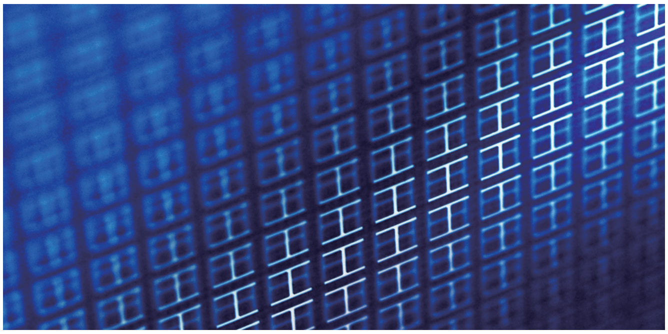

Figure 1. An illustration of an electromagnetic metamaterial.

The launch of this new field is marked by the famous paper by Sir John Pendry [1], published in the year 2000 after Veselago's visionary proposal on a similar topic had been neglected for over 30 years. Within 10 years of Pendry's paper, metamaterials became a breakthrough technology due to their potential for cloaking and light manipulation [2–6]. As this new technology takes shape, more and more applications have emerged in telecommunication, sensing, aerospace, optics (terahertz and infrared), and medical instrumentation. In addition to their industrial applications, metamaterials also show great potential for application in the military and in defense. The Defense Advanced Research Projects Agency (DARPA), the North Atlantic Treaty Organization (NATO), and major defense companies worldwide are all paying close attention to developments in this area [7–12].

This paper reviews metamaterials in academic research (Section 2) and in industry (Section 3), with a focus on state-of-the-art technologies in industrial applications (Section 3). We also share some of our own experience with the industrialization process and our view of the future development of this fascinating field (Section 4).

2 Academic research

After the early proof-of-concepts efforts, the second major phase of metamaterials development began with two papers, one by Leonhardt [13] and one by Pendry et al. [14], published in the same issue of *Science*. The introduction of transformation optics (TO) provided a design method for metamaterials, and that is the foundation of many research thrusts, such as cloaking and superlens research [4, 15, 16]. As powerful as the TO method is, it is limited in some aspects, one of which is the unrealistic properties generated after the space transformation. In addition, the approximation between the continuous properties from the design and the discrete properties from the implementation may affect the outcome when using the TO method. To address these limitations, constrained TO, or CTO, was developed. Where TO and CTO provide the blue print for designing metamaterials, the equivalent circuit

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Received 8 June 2015; received in revised form 20 June 2015; accepted 30 June 2015

method provides the building blocks. The equivalent circuit method enables fast topology selection and the optimization of micro-structures [17, 18], two factors that sometimes distinguish one design from another. The engineering electromagnetic community quickly adopted and developed low-profile antenna systems [19–21], beam steering systems [22], frequency-selective surfaces [17], structured surfaces [23], metamaterial-inspired antennas [24], radar-absorbing materials, and more. Another branch in electromagnetic metamaterials research was guided by the transmission-line method (TLM) [25]; with this method, leaky-wave antennas are able to scan from the backfire to the endfire directions [26, 27].

As Ziolkowski pointed out in Ref. [28], excitement about electromagnetic metamaterials was contagious in the optics community, leading to the development of optical metamaterials [29, 30]. Many ideas regarding hyperlenses and superlenses were carried out by researchers around the world [16, 31, 32]. Sophisticated electromagnetic modeling packages and powerful computation systems now make accurate simulation possible before fabrication is attempted. The achievement in the visible light spectrum was made possible and first reported by Dolling et al. in 2007 [33].

With continuing efforts in fundamental research on the theory and physics of metamaterials, functionalities were substantially enhanced when hybridizing functional matter with metamaterials. The use of microeletromechanical system (MEMS) was gradually applied to reconfigure metamolecules for electromagnetic [34] and terahertz metamaterials [35, 36]. Microfluidics was used to reconfigure microwave metadevices [37]. Gold metamaterial arrays fabricated on semiconductor substrates allowed real-time control of radiation with electric signals in 2006 [38]. As a 20–50 nm scale was achievable on the fabrication side [39], it was possible to fabricate a gold plasmonic nanowire pattern on a dielectric membrane that could be driven by external forces.

The achievements in metamaterials in the electromagnetic field inspired other researchers, branching the concept out to acoustics, water waves, plasmonics, and so on, which are governed by different mechanisms and equations [40, 41].

Among the research groups involved in metamaterials research, one group is particularly worth mentioning. The Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (Metamorphose VI), located in Europe, actively "integrates, manages, coordinates and monitors" research projects in the field of metamaterials, spreading excellence and transferring new technologies to industry.

In the US, the National Science Foundation (NSF)-backed Industrial/University Cooperative Research Center was established in 2002. The center is led by the City University of New York, and collaborates with academic institutions such as the University of North Carolina, industrial companies such as Raytheon, and technologists from across the metamaterials community. Current research projects at the center include the rapid prototyping and printing of tunable metamaterials as well as the development of modeling and design algorithms, active metasurfaces and metamaterials, conformal metamaterial antenna, and optical composite materials, all of which are fascinating and important aspects in the field.

3 Applications and industrialization

3.1 Early-stage applications

Today, a real demand exists for metamaterials in the market, for use in acoustics to terahertz and photonics. The metamaterial market can be categorized into five sectors: sensing, satellite communication (Satcom) and telecommunication, aerospace and defense, optics (terahertz and infrared), and medical instrumentation. According to a report (SE2430) from MarketsandMarkets in 2014, the market for metamaterials is expected to grow at a compound annual growth rate (CAGR) of 41% for the next 10 years.

In the sensing business, famous automobile manufacturers, such as Toyota and BMW, have expended significant efforts in the development of microwave and millimeter-wave metamaterials [42, 43]. According to the Toyota Central R&D Lab, metamaterials are expected to effectively contribute to automotive applications such as radar scanning systems, mobile communication antennas, novel magnetic materials for electric motors, and high-performance absorbing and shielding materials for electromagnetic compatibility (EMC) [42]. For conventional cruise-control and pre-crash safety systems, a field of view (FOV) covering about 20° over a range of 150 m at a millimeter-wave band (76–77 GHz) is sufficient. However, the new adaptive cruise-control and collision-avoidance assistance systems require a FOV of up to 60° over a range of 60 m. To fulfill these market requirements, Toyota developed a novel frequency-independent steerable composite right/left handed (CRLH) leaky-wave antenna with the advantages of wide beam steering, high gain and simple implementation. At Toyota, optical devices such as LED headlights and night-vision systems using infrared cameras are also expected to be targeted applications (Figure 2). High reflection and absorption from painted plastic fascia are issues that BMW must face when working on integrating millimeter-wave sensors from 77–81 GHz; these are common problems, due to the quasi-optical propagation properties at this frequency range. To this end, BMW has utilized impedance-matching techniques with metamaterials in order to smooth the transition from the bumper envi-

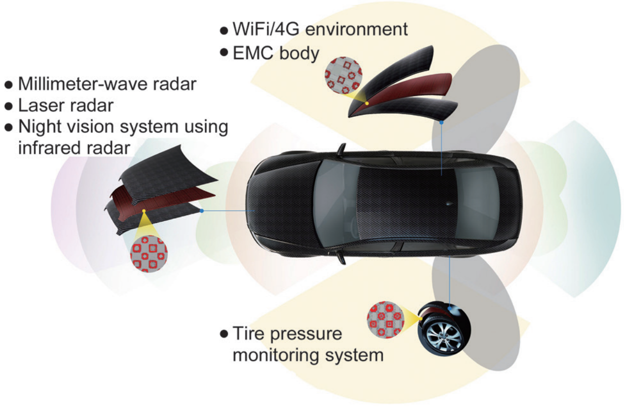

Figure 2. Industrial metamaterials for automotive applications.

ronment with high dielectric properties to free space [43]. Based on their measurements, the metamaterials achieved a reflection below –10 dB for a bandwidth up to 3.8 GHz, with a minimum reflection up to –25 dB; this reflection is 15 dB lower than that of traditional counterparts.

In the Satcom industry, a US company named Kymeta utilized a holographic approach to electronically steer a beam to a targeted satellite using electronically activated metamaterials [44]. The direction of the beam can be adjusted by precisely selecting the specific set of unit cells [45]. With a metamaterial approach, one can have an antenna with comparable performance to phased arrays at a much lower cost, since the whole transmit/receive (T/R) module can be eliminated. A flat, thin, lightweight and affordable reconfigurable holographic metamaterial antenna can be installed on aeroplanes, boats and regular vehicles. According to the Kymeta website, the company plans to release development kits to controlled customers and business partners this year, although the delivery date was previously set at late 2014. It seems that extra time is being taken for the transition from a laboratory prototype to an industrial product.

Regarding the infrared spectrum, metamaterials are being investigated to control the direction of thermal emission. Plasmonics Inc., a US company, collaborated with the US Sandia National Laboratories to take the advantage of the non-Lambertian emission profiles of metamaterials to design and fabricate directional emission surface. One potential application for this metasurface is for thermal management on satellites. To be more specific, the idea is to achieve high thermal emissivity from the satellite and, at the same time, high rejection of external heat loading from the sun. In other words, this concept utilizes the unique non-reciprocal thermal properties of metamaterials.

In the energy sector, wide application of solar energy is hindered by its high cost per kW·h output, which is approximately five times the cost of coal-generated electricity. Thin-film technology incorporated with metamaterial nanocomposites is utilized to substantially increase solar-cell efficiency by collecting light from wide angles and absorbing it over the spectrums of interest. This technology allows immediate use for existing solar panels with degenerating efficiency. Increased solar efficiency means a cost reduction per kW·h for customers and a profitability increase for solar farms. Commercial products are produced by a Canadian company named Metamaterial Technologies Inc. in collaboration with Professor Sandipan Pramanik et al. at the University of Alberta [46, 47].

For aerospace applications, nano-composites utilizing metamaterial technology are also used to selectively reject and control light coming from wide angles [48, 49]. One Canadian company recently announced a strategic partnership with Airbus to apply this technical innovation to the commercial aviation market. A thin-film metasurface is applied onto cockpit windscreens to selectively block certain spectrums, including the wavelengths emitted by high-power lasers. Their product line is estimated to launch in early 2016 after certain certificates are issued by regulatory authorities like the Federal Aviation Administration.

3.2 Driving applications

The exotic properties of metamaterials and their potential applications in cloaking quickly drew attention from agencies like DARPA. As early as 1999, DARPA began gathering information about metamaterials [28]. In 2001, the objective of the DARPA Multi-University Research Initiative (MURI) call for proposals (CFP) was "to model, synthesize, characterize and develop new synthetic metamaterials" [28]. With this request from DARPA, Boeing Phantom Works (now Boeing Research and Development) constructed their first 3D metamaterial, the Boeing cube, in 2003 [50]. DARPA has defined metamaterials as a "thrust area" and has provided continuous funding for metamaterial projects since 2000. According to the latest news, DARPA funding in this area has increased by 75% for the 2015 fiscal year. In addition to DARPA, the US Assistant Secretary of Defense for Research and Engineering (ASD R&E) has named metamaterials as one of six "disruptive basic research areas." The US Navy has issued over 60 Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) grants related to metamaterial technology for military use since 2006, most of which are in the Phase II and Phase III stages.

In Europe, NATO conducted a three-year research project on metamaterials for defense and security applications to assess trends in metamaterials and how they will impact NATO capabilities, starting in January of 2011. The six main topics that the study addressed are: ① radio-frequency (RF) metamaterial antennas; ② RF signature reduction; ③ thermal and infrared signature control; ④ metamaterials for imaging and sensing applications; ⑤ active, switching, nonlinear metamaterials; and ⑥ acoustic metamaterials. These six areas more or less cover the main research directions of metamaterials for military applications.

In terms of public open access, metamaterial technology has been used in various military devices and equipments on various platforms. Electromagnetic metastructures have been incorporated into the E2 Hawkeye rotodome to reduce unwanted aberrations caused by the presence of its structural ribs. Features of these metastructures include but are not limited to light weight, electromagnetic compatibility, retrofit capability, and satisfaction for the physical demands of the rotodome environment. The performance of other antenna systems encountering physical-structure interference with the propagation of electromagnetic signals can also be improved using similar approaches. Large-scale metamaterials with customized electromagnetic properties have been utilized for shipboard applications as well. The novel properties of these materials provide more options to solve complex electromagnetic problems. With new metamaterial manufacturing and assembly processes, technologies including low-profile antennas, exotic waveguides, and large-area metamaterials with reduced communication interference, enhanced radar absorption, and improved impedance match have all made their debuts on US Navy ships.

3.3 Industrialization

As Ziolkowski from the University of Arizona stated in the new journal *Applied Metamaterials* in 2014, once metamaterial researchers understood the basics, subsequent years saw a transition into potential and actual applications [28].

Commercialized software introduced specific modules for metamaterial simulation. As early as 2006, Feko produced application notes for the analysis of negative index materials. One year later, Ansoft compiled a white paper called the *Left-Hand Metamaterial Design Guide*. Recently, computer simulation technology (CST) focused on the modeling and simulation of metamaterial-based devices for industrial applications [51]. With the advancement of software and hardware in parallel computing and clusters, the simulation of electrically large metamaterial-based and/or metamaterial-inspired devices and equipments is viable and cost-effective.

For the industrialization of metamaterial technology, mass production on conformal structures is a major challenge. For optical metamaterials, researchers in nanotechnology and microtechnology utilized deposition, electron-beam lithography, atomic sputtering, and self-assembly methods to fabricate structures smaller than wavelength. The incorporation of semiconductors and their technologies into metamaterials can realize exotic tunabilities. Direct writing, laser engraving and standard lithographic techniques are employed for the large-scale production of microwave metamaterials. SI2 Technologies, Inc. in Massachusetts, USA developed direct inkjet systems that can print electronic circuits on flexible or curved surfaces at low temperature. The conformal nature and roll-to-roll volume of these circuits provide significant advantages for avionics integration.

Metamaterials research and development are the core of the Kuang-Chi Research Institute of Advanced Technology (referred to as Kuang-Chi). Kuang-Chi is intended to establish the connection between fundamental research and industrial implementation. Based on its many years of practice in the metamaterial market, Kuang-Chi has created its industrialization architecture, shown in Figure 3. Under this architecture, real demands are introduced from the market and clients, and filtered based on specific criteria. Metamaterial products are then designed by order using our key technologies. Using these procedures, we have extended our technologies for use in near-space communication, satellite communication, airborne/carborne RF systems, wireless coverage for subway systems, and more. Kuang-Chi has filed as many as 2934 patent applications so far and been granted over 1200 patents.

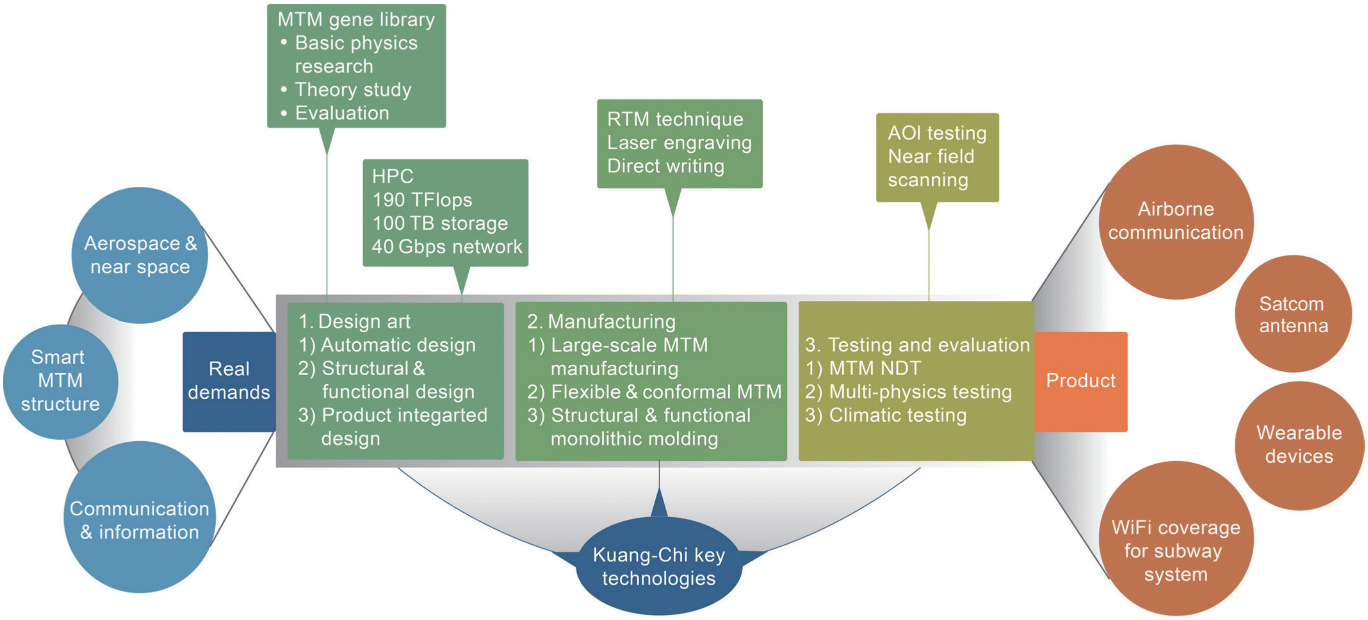

Figure 3. The industrialization architecture of Kuang-Chi metamaterial research. MTM: metamaterial. HPC: high power computing. RTM: resin transfer molding. AOI: automated optical inspection. NDT: non-destructive testing.

To the best of our knowledge, we introduced the first metamaterial-based Satcom antenna to the world in 2011. Thanks to its gradient index design (GRIN), the reflector of this antenna has a planar shape that is only 2 mm thick. Since then, these products have been installed in over 22 cities across China for residents in rural areas. Figure 4 shows an illustration of a portable metamaterial Satcom antenna in a suitcase. In addition, we recently launched "the Traveler" in New Zealand; this carrier is a near-space platform integrated with metamaterial technologies for communication, monitoring and remote sensing. This is the first time that China has launched a near-space vehicle in a foreign country.

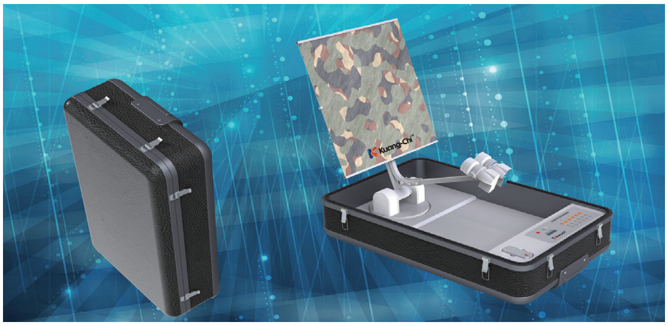

Figure 4. The Kuang-Chi flat-panel reflector antenna for Satcom, in a suitcase.

4 Development and future

As the comprehensive review by Kadic et al. titled *Metamaterials beyond electromagnetism* points out, the metamaterial concept also applies to thermodynamics and classical mechanics (including elastostatics, elastodynamics, acoustics, and fluid dynamics) [41]. As optical metamaterials and electromagnetic metamaterials develop and flourish, other related areas are envisioned to grow rapidly as well.

There is no doubt that controllable metamaterials, upon which smart structures and smart skin will be built upon, will be the trend of the next phase of metamaterial development. With these materials and technologies, bullet trains and recreational vehicles (RVs) will be able to receive a stable media stream throughout a journey by sensing the strongest signal.

In the future, metamaterial design will be more challenging than ever before. Structural and functional properties will be bound more and more closely together. As flexible as the microstructure design is, it must face physical boundaries such as mechanical properties, thermal properties, environmental properties, and manufacturing tolerance. A cross-disciplinary, multi-physics and multi-model design on the proof-of-concept, product and system levels will be very intriguing in material science.

5 Conclusions

In this article, we review the development of metamaterial technology in academic research and in industry. The ability to control and manipulate electromagnetic, optic, and acoustic waves differentiates metamaterials from traditional materials. With their tunability, metamaterials will be able to adjust transmission, reflection and absorption, steer beam direction, control heat conduction, and more. They will even be able to sense and respond without human interference.

Metamaterials have reshaped material science. It is time for us to rethink their abilities.

Acknowledgement

This study was supported by Guangdong Innovative Research Team Program (2009010005).

Compliance with ethics guidelines

Ruopeng Liu, Chunlin Ji, Zhiya Zhao, and Tian Zhou declare that they have no conflict of interest or financial conflicts to disclose.

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