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Editorial

Metamaterials: From Engineered Materials to Engineering Materials

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As a new frontier in materials science, metamaterials have experienced a boom in the past two decades. This research field began with artificially structured materials exhibiting extraordinary electromagnetic properties unavailable in nature; now, it extends to a large family of artificial-material systems with wide-ranging, extraordinary, and outstanding properties for applications in fields such as electromagnetics, optics, mechanics, thermodynamics, and acoustics, based on engineered functional units instead of inherent characteristics. The focus of metamaterial research has eventually shifted from new principles, new phenomena, and new structures to new properties and new functions for technological applications. Metamaterials are increasingly anticipated to provide technological solutions to many challenges in engineering. The nature of metamaterials is transforming through an evolutionary process from engineered materials to engineering materials. This special issue reflects on some clues to this historical process.

Inspired by the realization of negative-index materials, the first metamaterial was born at the end of the 20th century. Two significant inventions by Sir John Pendry took the lead in achieving supernatural properties artificially. In the first of these inventions, metal wires exhibited an effective negative permittivity at a low plasma frequency; in the second, a split ring resonator mimicked the circulating current in a molecule, enabling the generation of artificial magnetism. These inventions directly paved the way for the achievement of a negative index with negative permittivity and permeability; they also helped in developing the idea of achieving physical properties beyond those present in nature through artificial structures with engineered units. Pendry's successful demonstrations not only provided an astonishing illustration of negative refraction, but also enlightened researchers on the fact that there was a method to artificially manipulate permeability. In the same way, Pendry's work on the refractive index brought in a series of novelties. The negative index itself can be used as a perfect lens that can break the diffraction limit in microscope imaging. In addition, a metamaterial with a desired refractive index distribution can guide light beams to pass around a central region that is thereby rendered invisible to the light, in what is called "cloaking." Other achievements, such as the metamaterial absorber, zero-index material, and electrical-induced transparency can also be attributed as the designable ε and μ. These works emerged during the ten-year period immediately after metamaterials were first proposed. During that decade, metamaterials flourished in electromagnetics and expanded to optics as well.

With the success of this concept, properties beyond those that appear in nature are not limited to electromagnetics or optics. Metamaterials are also boosting innovations in mechanics, acoustics, and thermodynamics, pushing new boundaries in the entire realm of physics. During the last 20 years of progress, the design ideology and fabrication techniques for metamaterials have been well developed. From a scientific perspective, metamaterials supply a very powerful platform to nourish new physics; from an engineering perspective, they are now a well-established tool, ready for real applications. Researchers are paying increasing attention to functionalities that can significantly improve current technologies; thus, these engineered materials are transitioning from scientific research to the field of engineering. In this special issue, we introduce recent achievements from several top research groups in the field of metamaterials to report on promising applications of metamaterials and metamaterial-based devices in engineering.

Microwave metamaterials have been the most extensively studied metamaterials, since they were the first realization of the concept of a metamaterial. Many new electromagnetic effects were also demonstrated for the first time in the microwave range, mainly to obtain material properties that do not show up at high frequencies or to avoid fabrication issues from nanofabrication. Nowadays, microwave metamaterials are also the closest in the metamaterials family to achieving real applications and being used industrially, especially in communication engineering. In this special issue, we reveal a very smart design for an information meta-

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surface consisting of a digital reconfigurable antenna array by Prof. Cui's group at Southeast University in China. This work not only provides a very intriguing design for realizing digital coding through a metasurface, but also includes a series of serious characterizations, through which the design's performance is shown to be so excellent that this device is ready for application in radar and wireless communication systems.

In the field of optics, Prof. Gan's group at the State University of New York at Buffalo and their collaborators at Northeastern University bring us an interesting design for biosensing: a plasmonic resonance-based metamaterial device with ultra-high spectral resolution. In their design, "rainbow" coupling from the plasmonic grooved structure is used to achieve an extremely strong dispersive response of the light. The design, which is fairly compact in size, is demonstrated as a chip-size sensor in exosomal epidermal growth factor receptor (EGFR) for lung cancer diagnosis.

Nonlinear light and matter interaction is always a hot topic in the field of optics. Prof. Litchinitser's group at Duke University is one of the top groups working on the nonlinear effects of light in metamaterials. In this special issue, Prof. Litchinitser presents a perspective on the modulation instability (MI) of structured light, which has angular momentum or cylindrical vector polarizations in saturable media—a type of engineered liquid material with suspended particles, which simulates a turbid environment such as underwater, fog, clouds, or biological tissues. The nonlinear effects of self-focusing, MI, and spatial soliton formation are always involved in saturable media. This study also aims at optical applications in science and technology, including bioimaging, underwater applications, and free-space communication.

Sound is another critical aspect of nature, and metamaterials can play a role in acoustic engineering. We include in this issue a perspective paper from Prof. Chen's group at Nanjing University, which describes the applications of acoustic metamaterials in future engineering, such as sound isolation, acoustic imaging, and cloaking, some of which have been explored in recent years. These application scenarios are not only in air, but also underwater and even within human bodies.

The ancient paper-folding art of origami has gained popularity in recent years among researchers, inspiring many innovations in mechanical metamaterials. In this special issue, we include an research article from Prof. You's group at University of Oxford, introducing a programmable origami metamaterial. They report that a combination of rigid and non-rigid origami units can greatly improve the mechanical properties of the proposed metamaterial. Moreover, with the tessellation rule, the properties of the metamaterial are predictable and controllable. The reported metamaterial has a form of pixelation, which makes it programmable; as a result, it can be customized into a desired state. This metamaterial thus holds great significance for engineering applications.

Finally, a comprehensive review paper from Prof. Zhang's group at Wuhan University of Technology outlines recent progress in mechanical metamaterials, including stiff and strong materials and the properties of metamaterials with various topologies. The paper also discusses current challenges and recommends future directions for mechanical metamaterials through additive manufacturing technologies.

After almost 20 years' accumulation of deep and extensive studies, basic theories have been extensively and deeply explored, and general processes for metamaterial design and fabrication are well established. We can imagine how these engineered materials will lead to an increasing number of achievements in engineering, greatly changing the world in the future.