Ceramic-based dielectric metamaterials

Weijia Luo | Sen Yan | Ji Zhou

State Key Laboratory of New Ceramics and Fine Processing, School of Materials Science and Engineering, Tsinghua University, Beijing, China

Correspondence
Ji Zhou, State Key Laboratory of New Ceramics and Fine Processing, School of Materials Science and Engineering, Tsinghua University, 100084 Beijing, China.
Email: zhouji@tsinghua.edu.cn

Funding information
Basic Science Center Project of NSFC, Grant/Award Number: No. 51788104

Abstract
Dielectric metamaterials based on ceramics have attracted considerable interest in the past few years owing to their low dielectric loss, simple structure, excellent multifield tunability, and good environmental adaptability. They are considered to be promising alternative to metal-based metamaterials and can lead to a new strategy for the development of passive devices. In this review, the recent progress of ceramic-based dielectric metamaterials in electromagnetic applications, energy applications, non-Hermitian systems, and natural materials with near-zero or negative refraction are summarized. The design principle and mechanism, as well as manufacturing technologies, are also introduced, and the current development trend of ceramic-based dielectric metamaterials are proposed.

KEYWORDS
ceramic-based, interdisciplinary materials, metamaterials, multifunctional applications, new physics

1 | INTRODUCTION

Early research on metamaterials with artificial structures originated from the extraordinary physical properties that do not exist in natural materials, including near-zero or negative refractive index, enhanced transmission or absorption, reversed Doppler shift, and perfect lens behavior.

Currently, their novel physical properties and applications have extended to multiple domains, then the generalized metamaterials are gradually defined as multifunctional and periodic or randomly distributed arrays, and methods to further improve the applicability of metamaterials have become an important topic. In the past few years, many new devices, such as enhanced antennas, perfect absorbers, invisible devices, highly sensitive biosensors, and filters based on electromagnetic metamaterials have been developed in various fields, which exhibit significant advantages.

Nevertheless, most of them are currently based on metal resonant structures or cells, and the high energy dissipation of metal hinders further applications of relevant metamaterial devices, particularly at higher frequencies.

Fortunately, owing to the combination of Mie theory and effective medium theory, metamaterials based on dielectric resonance are expected to provide a new implementation path, attracting considerable interest in many innovative fields. From the early research on Hermitian systems to the more recent research on non-Hermitian (NH) systems, an increasing number of novel physical phenomena have been discovered owing to the introduction of loss and gain, which provides a larger creative space for dielectric metamaterials. Then, related devices combined with the resonance effect have emerged at different frequency bands, also in different fields. Here, we mainly discuss ceramic-based dielectric metamaterials with ceramic as the unit cell. The main components are
ceramics with high permittivity or other prominent functional parameters (e.g., ferroelectric, piezoelectric, dielectric, and magnetic properties) for different resonance effects. Compared to the construction of discrete component (capacitance or inductance) structures in metal-based metamaterials at high frequencies, a single dielectric ceramic block can realize the basic resonance function, indicating that the structure of ceramic-based dielectric metamaterials is simpler and the preparation is more convenient.\textsuperscript{[11–13]}

At the beginning of the 20th century, early ceramic-based dielectric metamaterials are mainly used in electromagnetic applications. In previous studies, ceramics with high permittivity, such as (Ba, Sr, Ca) TiO\textsubscript{3}-based ceramics, are mainly concentrated in the microwave range. The metamaterial unit cells can overcome the limitations of loaded metal devices and maintain exploitable resonance modes, with the advantages of subwavelength size, low power consumption, flexible structural design, and versatility.\textsuperscript{[14–16]} Furthermore, the strong coupling between different resonant modes limited to the ceramic unit cells, the weak coupling between unit cells due to near-field interactions, and the coupling between structures related to Mie resonance and the inherent resonant modes (such as ferromagnetic resonance and lattice resonance), indicating that this type of metamaterials may develop extremely rich new functionalities that metal-based metamaterials lack.\textsuperscript{[19–21]} Today, it has been widely used in resonators, filters, duplexer, absorbers, and enhanced antennas that cover both the microwave and terahertz range.\textsuperscript{[22–24]} In recent years, dielectric metamaterials based on ceramics find a new direction in NH systems. For instance, the mode coupling can be modified by adjusting the loss and structure of the ceramic unit cell to achieve properties that are not possible in Hermitian systems, and additional topological structures with specific functionalities will be designed and fabricated in the future, which are expected to be applied to a variety of devices based on quantum mechanics, such as optical switches, coherent perfect absorbers, and high-resolution sensors.\textsuperscript{[25,26]} In addition, ceramic-based dielectric metamaterials are no longer limited in electromagnetic applications at present. With the continuous development of ceramic materials and preparation methods, the corresponding physical and chemical properties are controllable, then trigger an upsurge of research on ceramic-based dielectric metamaterials in more fields. Recently, they also exhibit many advantages for energy conversion and other fields through rational structural design, for the high temperature stability and energy absorption efficiency, adjustable components or microstructure, good machinability, and easy-to-implement.\textsuperscript{[27–29]} In the development of new applications and new physics, ceramic-based dielectric metamaterials are constantly creating new possibilities.

In this review, we outline the progress in the field of ceramic-based dielectric metamaterials over the past few years, as the following aspects shown in Figure 1.

The purpose is to fully prove that, from new physical foundations to application directions, ceramic-based dielectric metamaterials deserve more attention. In particular, the continuous development of mode coupling theory and practical NH systems will result in more novel physical phenomena for flexible design and material selection. Finally, following the development trend of modern physics, multifunctional devices that realized only by ceramic-based dielectric metamaterials are expected to flourish. They will be integrated with many other devices and have wide application prospects in the future.

2 | CERAMIC-BASED DIELECTRIC METAMATERIALS IN ELECTROMAGNETIC APPLICATIONS

Ceramic-based dielectric metamaterials for electromagnetic applications are the most widely studied at present, in which the resonance characteristics of dielectric ceramics are reasonably utilized, including resonators, filters, duplexer, absorbers, and enhanced antennas that cover both the microwave and terahertz range. Compared with metal-based devices, their relatively high performance and simple structure are of great significance for the development and miniaturization of high-frequency wireless technology in the future.\textsuperscript{[22–24]} The typical applications are introduced in the following sections.

2.1 | Microwave absorbers

In electromagnetic applications, Mie theory and effective medium theory can yield numerous special electromagnetic response phenomena, resulting in a large
number of electromagnetic devices. For example, microwave absorbers can be realized by the intense Mie resonance originating from dielectric ceramics with a high permittivity. They are based on strong ion displacement polarization in the microwave range. Referring to the complex chemical bond theory for oxide ceramics, Ba$^{2+}$, Sr$^{2+}$, and Ca$^{2+}$ ions can provide high polarizability. Thus, (Ba, Sr, Ca)TiO$_3$-based ceramics with perovskite structure are the most commonly used, because they possess high permittivity (>100) and provide good conditions for the generation of displacement current.\textsuperscript{[30–33]}

According to Mie theory and the multistage expansion based on electrodynamics theory, the spherical model is the most basic research object, and the Mie resonance of a ceramic sphere can be divided into electric resonance and magnetic resonance.\textsuperscript{[34–36]} Taking the magnetic resonance as an example, the first-order magnetic Mie resonant frequency of a ceramic sphere and the corresponding derivation are given in Equations (1)–(3), which are from the report by Wheeler et al.,\textsuperscript{[37]} and they are also utilized as a guide for ceramic blocks. In the microwave range, considering a nonspherical ceramic sphere with relative permeability $\mu_b = 1$, relative permittivity $\varepsilon_s = n_s^2$, and radius $r_s$ in free space ($n_b = 1$), the magnetic dipole portion of the scattered field is proportional to:\textsuperscript{[38]}

$$\psi = \frac{n_b \psi_1(x_b) \psi_1'(x_b) - n_s \psi_1(x_b) \psi_1'(x_s)}{n_b \psi_1(x_s) \xi_1'(x_b) - n_s \xi_1(x_b) \psi_1'(x_s)},$$

(1)

where $x_b = n_b k_0 r_s$, $x_s = n_s k_0 r_s$, and $\psi_1(z)$ and $\xi_1(z)$ are the Riccati–Bessel functions. The magnetic polarizability $\alpha_m$ of the sphere is defined as follows:

$$\alpha_m = \frac{6 \pi i}{k_0^3} b_1.$$

(2)

Equating the denominator of Equation (2) to zero and using the long-wavelength condition $x_b \ll 1$, the resonant frequency $f_m$ of the first magnetic dipole resonance can be approximately calculated by the following equation:

$$f_m = \frac{c}{2 n_s r_s},$$

(3)

where $f_m$ is the resonant frequency of the first magnetic resonance, $c$ is the speed of light, and $n_s$ is the refractive index. The electric Mie resonance can also be obtained using a similar method to the derivation above.

After adding the influences of the surrounding environment, effective medium theory is introduced to describe the overall electromagnetic responses of dielectric metamaterials. Then, the effective permittivity $\varepsilon_{\text{eff}}$ can be expressed as follows:\textsuperscript{[39]}

$$\varepsilon_{\text{eff}} = \varepsilon_1 \left( 1 + \frac{3 \varepsilon_f}{F(\Theta) + 2b_n F(\Theta) - b_n} \right),$$

(4)

The effective permeability $\mu_{\text{eff}}$ can be deduced as follows:

$$\mu_{\text{eff}} = \mu_1 \left( 1 + \frac{3 \mu_f}{F(\Theta) + 2b_m F(\Theta) - b_m} \right),$$

(5)

where $F(\Theta)$ is calculated using Equation (6):

$$F(\Theta) = \frac{2 (\sin \Theta - \Theta \cos \Theta)}{(\Theta^2 - 1) \sin \Theta + \Theta \cos \Theta}.$$

(6)

Here, lossless magnetodielectric spheres ($\varepsilon_2$ and $\mu_2$) are embedded in another background matrix ($\varepsilon_1$ and $\mu_1$). Then $b_c = \varepsilon_1/\varepsilon_2$, $b_m = \mu_1/\mu_2$. $\varepsilon_f$ is the volume fraction of the sphere, and $\mu_f = k_0 \varepsilon_0 \varepsilon_2 \mu_2$. $r_0$ is the radius of particle. Theoretically, with a sufficiently high effective permittivity, the ideal absorbance of a single resonant mode (electric or magnetic) can reach a maximum value of 50%. To achieve perfect absorption, this value must be doubled, which requires a metal reflector. Liu et al.\textsuperscript{[22]} verified this type of metamaterial perfect absorber from design to experiment. It was composed of SrTiO$_3$ ceramics, where the “meta-atoms” were embedded in a background matrix on a metal plate, as shown in Figure 2.

With specific structural dimensions, the high permittivity could effectively bind the electromagnetic energy, and the metal plate could attenuate the transmission part. Then, the microwave absorbance could be calculated using Equations (7)–(9).

$$A(\omega) = 1 - R(\omega) - T(\omega),$$

(7)

$$R(\omega) = |S_{11}(\omega)|^2, T(\omega) = |S_{21}(\omega)|^2,$$

(8)

$$A(\omega) = 1 - R(\omega) = 1 - |S_{11}(\omega)|^2.$$

(9)

The absorbance $A(\omega)$ could be obtained from reflectance $R(\omega)$ and transmittance $T(\omega)$, from the $S_{11}$ and $S_{21}$ parameters measured by a vector network analyzer. For the ABS substrate, $\varepsilon_1 = 2.67$ with loss tangent $\tan \delta_1 = 0.006$, which was used to fix the position of the “atoms,” and the dielectric properties of SrTiO$_3$ were $\varepsilon_2 = 341$ and $\tan \delta_2 = 0.002$. In the measurement process, two linearly polarized focused antennas were connected to a vector network analyzer, with a low-loss coaxial
cable to emit and receive electromagnetic waves in the frequency range of 8.2–12.4 GHz. The metamaterial was placed at the focus of the antennas in a microwave anechoic chamber. Then, an absorption peak with $A = 99\%$ at 8.96 GHz was obtained, exhibiting nearly perfect microwave absorbance in the X-band with good adaptability for wide-angle incidence, the size of the resonant unit cells was approximately 1/18 the modulation wavelength. Based on these results, ceramic-based dielectric metamaterial absorbers operating in multiple modes have attracting significant attention. In addition to the single magnetic resonance mode upon, the electric resonance or matching resonant unit cells with different sizes can also be utilized for perfect absorption to achieve a dual-band or multiband metamaterial perfect absorber, which can be adapted to different application requirements.$^{[40,41]}$

### 2.2 Microwave filters

Another major electromagnetic device is the filter, and filters based on ceramic-based dielectric metamaterials are also important. Through Mie resonance, this type of metamaterial can selectively transmit electromagnetic waves at a specific frequency. Li et al.$^{[23]}$ developed band-pass frequency selective surfaces (FSSs) using high-permittivity ceramics $(0.7\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3-0.3\text{La} (\text{Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ $(\varepsilon_r = 110$ and $\tan\delta = 0.0015)$ based on effective medium theory and dielectric resonator theory, the H-shaped structure is shown in Figure 3. The test method was similar to that of the “meta-atoms,” in which horizontally opposed rectangular waveguides were used to determine the S parameters. In the frequency range of 10.5–11.9 GHz, there was a high-efficiency pass band, and the insertion loss was below 0.5 dB. Owing to processing error and other factors, the experimental measurements differed slightly from that of the simulation, but it essentially realized broadband filtering. Moreover, this metamaterial also had good temperature stability in the microwave range, which was attributed to the near-zero temperature coefficient of the $0.7\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3-0.3\text{La} (\text{Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ system.$^{[42]}$ Thus, it is expected that the practical application of this type of metamaterial filter will be promoted in the future, particularly in extreme environments.

As another solution, ferrite is commonly used in magnetically tunable wideband microwave filters owing to its magnetic response at microwave frequencies. Bi et al.$^{[43]}$ embedded yttrium iron garnet (YIG) rods in a Teflon substrate to fabricate a metamaterial, as shown in Figure 4. In this system, the negative permeability appeared around the ferromagnetic resonance frequency. It led to a remarkable stopband, allowing the formation of a band-stop filter. Under an external magnetic field in the range 2000–2600 Oe, the stopband center frequency distributed at the range of 8.75–10.37 GHz, tuning at a rate of 2.7 GHz kOe$^{-1}$.

Furthermore, the magnetically tunable property derived from the coupling of the dielectric and magnetic parts of the Mie resonance is also valuable. The authors established the resonance unit cells using a dielectric cube and ferrite cuboid (as shown in Figure 5), the test system is represented in Figure 6.$^{[44]}$ Both the simulated and experimental results indicated that the effective permeability and permittivity of the metamaterial could

![Figure 2](image-url) (A) The designed dielectric metamaterial absorber and its unit cell. (B) Dielectric metamaterial absorber sample$^{[22]}$ Copyright 2016, Optical Society of America

![Figure 3](image-url) Unit cell of the all-dielectric band-pass frequency selective surface$^{[23]}$ Copyright 2016, AIP Publishing
be tuned by modifying the applied magnetic field. This study offers a promising method for constructing microwave devices with large tunable ranges and a considerable potential for tailoring via a ceramic-based dielectric metamaterial route.\(^{43}\)

2.3 | Terahertz devices

Above the microwave band is the terahertz band, which is becoming increasingly important, and Mie theory and effective medium theory remain applicable in this band. For the fabrication of ceramic-based dielectric metamaterials in the microwave range, wire cutting with relatively good precision is sufficient. However, to meet the subwavelength requirements in the terahertz range, the preparation process of ceramic-based dielectric metamaterials becomes challenging, particularly for large-scale metamaterials with fine unit cells approaching metasurfaces.\(^{19}\) Furthermore, the terahertz band is close to the intrinsic vibration frequency band of molecular chemical bonds in dielectric ceramics. Consequently, it is difficult to obtain a large permittivity like that in the microwave band, and the increased dielectric loss also deteriorates the electromagnetic properties of ceramic-based dielectric metamaterials.\(^{45}\) Thus, the selection of ceramics is relatively
limited: zirconia and alumina are currently the most commonly used. Furthermore, some ferrites still have weak magnetic response in this frequency band, such as TbFeO₃, which is also utilized to fabricate ceramic-based dielectric metamaterials in the terahertz range.

Gao et al. successfully prepared submillimeter ZrO₂ microspheres, which they used to design and realize a new Mie-resonance terahertz absorber. The ZrO₂ microspheres were prepared by the reactive spray atomization method. First, zirconia sol was sprayed into an aqueous ammonia solution, after which the gel precipitate was dried and calcined. The gel particles preserved a spherical shape because of a thin solid film that formed on the droplet surface via contact with gaseous ammonia before impact with the ammonia solution. After they were dried and calcined, the gel spheres transformed into solid free-flowing powders. After sieving, the ZrO₂ microspheres meeting the size requirements were obtained. Using this method, the diameters of the ZrO₂ microspheres were in the range of 120–150 μm, and the average diameter was approximately 130 μm. The permittivity of the ZrO₂ microspheres was 32.5, and the loss factor (tanδ) was approximately 0.05 at 3 THz, which can realize Mie resonance in the terahertz range.

On this basis, the preparation of large-scale terahertz metasurfaces was further studied. For instance, Bi et al. developed a microtemplate-assisted self-assembly (MTAS) method to prepare ultra-large-scale flexible ceramic microsphere all-dielectric metamaterials with high precision, the area exceeded 900 cm × 900 cm. A comparison of this method with the nano-template-assisted self-assembly (NTSA) method is provided in Figure 7. In the MTAS method, a soft slicker was used to move the microspheres from left to right. The microspheres were pushed into the preset holes and assembled by the external forces (Fₑ) and gravity (F₉). Then, a thin adhesive layer was applied between the microtemplate and the substrate. Finally, the template was removed and a precise ceramic microsphere-based metamaterial or metasurface was obtained.

On the basis of MTAS method, the authors used Al₂O₃ and ZrO₂ ceramic microsphere resonators to fabricate metamaterials. As shown in Figure 8, the dimer, trimer, quadrumer, and chain configurations could be obtained by using the proper template. A broadband reflector with a bandwidth of 0.15 THz and a reflection of up to 95% was successfully realized, proving the reliability of this method.
Moreover, laser processing and 3D printing are also effective methods to fabricate terahertz ceramic-based dielectric metamaterials. As shown in Figure 9, Zeng et al. [24] developed a type of metamaterial using the typical ferrite TbFeO$_3$, in which the central symmetry and central symmetry breaking of unit cells could be used to tune the terahertz transmission frequency. They also demonstrated that laser beam machining is an efficient and easy method for fabricating terahertz ceramic-based dielectric metamaterials. Furthermore, with the development of 3D printing technology, ceramic printing is possible. The authors also explored a 3D direct writing technology to fabricate TbFeO$_3$ metamaterials, as shown in Figure 10. [51] After the 3D direct writing process, the as-fabricated structures were dried at 80°C for 24 h in an oven and then transferred to a muffle furnace for sintering. During sample measurements, the desired strong electric and magnetic resonances were effectively excited, presenting increased polarization-dependent transmittance as the line spacing decreased. The face-centered cubic (fcc) metamaterial exhibited a deep transmission drop at low frequencies and an electromagnetically induced increase in transmittance at higher frequencies. Moreover, owing to the characteristics of TbFeO$_3$, this metamaterial also exhibited a certain thermal tunability, enabling terahertz tunable devices.

Currently, owing to the advantages of ceramic metamaterials, they are gradually moving toward industrialization and have broad application prospects in the future,
particularly in the wireless communication field. However, to meet the development requirements for multiband applications, the corresponding ceramic systems require further development.

3 | CERAMIC-BASED DIELECTRIC METAMATERIALS FOR ENERGY APPLICATIONS

As energy problems become increasingly prominent, solar-to-thermal technologies can provide cost-effective solutions. Currently, low-cost and large-area solar-thermal absorbers with superior spectral selectivity and excellent thermal stability are urgently needed, particularly for space heating, desalination, ice mitigation, photothermal catalysis, and concentrating solar power.\(^5\) Owing to their flexible structural design, tunable performance, and low cost, metamaterials are increasingly used in solar energy applications; for example, solar absorbers have been applied for solar-thermal energy conversion.

Based on the background above, plasmonic metamaterials are the main research focus for these applications rather than the Mie-resonance-based class. The principle is based on the generation of plasma by the interaction between light and metal-dielectric materials. After it is incident on a plasmonic metamaterial, light can be transformed into plasma polarized light with a considerably shorter wavelength than that of the incident light, which can overcome the limitation of the wavelength of the original light and effectively improve absorption performance. Current research mainly focuses on the simplification of the metamaterial manufacturing process, development of new metamaterial structures and nanostructures, design and measurement of novel properties, as well as development of microscopes beyond diffraction limits.\(^5\)
Early metal–dielectric-based plasmonic metamaterials were generally made of lithographically patterned or short-term sputtered metallic nanoparticles, which have been proven to provide tunable optical absorption via structural design and engineering.\(^\text{[58,59]}\) For typical metals, such as Au (1063°C) and Ag (961°C), the melting points are also not high enough, which limits the absorption performance. Therefore, high melting point transition metals, such as W, Mo, and Ta, are preferred. However, the subsequent problems of high cost and impedance mismatch in the visible region are difficult to solve.\(^\text{[60]}\) Furthermore, for plasmonic metamaterial absorbers in solar–thermal systems, the overall performance is highly dependent on their stability and solar-to-thermal energy conversion efficiency as solar absorbers, which can be expressed as\(^\text{[61]}\).

\[
\eta_{\text{solar-th}}(T) = \bar{\alpha} - \bar{\varepsilon} \frac{\sigma (T^4 - T_0^4)}{C \times I_{\text{solar}}} , \tag{10}
\]

where \(I_{\text{solar}}\) is the total solar radiation (AM 1.5 G, 1 sun or 1 kW m\(^{-2}\)), \(C\) is the concentration ratio, \(\sigma\) is the Stefan–Boltzmann constant, \(T\) is the operating temperature, \(T_0\) is the ambient temperature, \(\bar{\alpha}\) and \(\bar{\varepsilon}\) are the spectrally averaged solar absorptance and IR emittance, respectively. Physically, radiative heat loss is another challenge for achieving high \(\eta_{\text{solar-th}}\). With the development of dielectric ceramics, conductive ceramics with high sintering temperatures and melting points are expected to replace the use of metals. Furthermore, their low loss can also alleviate the problem of heat loss. Here, novel all-ceramic plasmonic dielectric metamaterials are the main focus, and their energy applications are introduced, particularly for solar energy absorption and conversion in high-temperature environments.\(^\text{[62,63]}\)

At present, Li et al.\(^\text{[52]}\) prepared an all-ceramic plasmonic dielectric metamaterial by spontaneously assembling colloidal titanium nitride (TiN) nanoparticles into an ultrathin film on a reflective substrate (TiN) to form an asymmetric Fabry–Pérot cavity, as shown in Figure 11. Without a dielectric spacer, its structure differed from the traditional metal/insulator/metal structure of plasmonic metamaterial absorbers. Consequently, it could be fabricated by facile and scalable solution-based approaches, such as spin coating. This design enabled synergetic coupling between the in-plane plasmon resonance of the nanoparticles and the out-of-plane Fabry–Pérot resonance of the nanoparticle film and reflector, achieving near-perfect absorption over the full sunlight spectrum (\(\bar{\alpha} \approx 95\%\)) and low mid-IR (MIR) emission (\(\bar{\varepsilon} @ 100^\circ\text{C} \approx 3\%\)) with an approximately 120 nm thick nanoparticle film. Moreover, because all the components were ceramics, it exhibited excellent stability up to 727°C, and the cost of lab-scale sample was only approximately 1.59 USD m\(^{-2}\). In conclusion, compared with traditional metal/insulator/metal plasmonic metamaterial absorbers, the all-ceramic design has comprehensive advantages.

Moreover, in addition to the TiN ceramic, numerous other ceramic systems have been demonstrated to have application prospects in the field of solar energy absorption and conversion, such as ZrB\(_2\), Ti\(_3\)C\(_2\), and TiB\(_2\).\(^\text{[64–66]}\) This combination of ceramic-based dielectric metamaterials and energy applications is a new field and requires further meaningful research.

4 | CERAMIC-BASED DIELECTRIC METAMATERIALS IN NH SYSTEMS

The further development of metamaterials requires continuous innovation of physical theory. Recently, non-linearities have been realized in generalized metamaterials, such as topological photonics. When invoked, they can offer a dynamic tuning mechanism that produces various exotic phenomena, including robust discrete solitons, self-localized topological edge solitons, topologically enhanced harmonic generation, optical isolation, topological lasers, and self-induced topological states.\(^\text{[67–75]}\)

Currently, NH systems provide a new perspective for the development of ceramic-based dielectric metamaterials.\(^\text{[76–79]}\) Through ion doping and structural regulation, the great variety of dielectric ceramics can increase the designability of loss in NH systems. Furthermore, unit cells based on dielectric ceramics can accommodate multiple resonant modes that differ from metals, thus more exceptional designs that trigger novel NH physics are expected to be found and regulated. Here, the Su–Schrieffer–Heeger (SSH) 1D chain, which was first used to describe the fractionalized charges in polyacetylene that appear in the presence of a dimerization defect, is utilized to examine the interplay of non-linearities with non-Hermiticity and topological protection.\(^\text{[60]}\) Currently, the regulation of the physical properties of ceramic-based dielectric metamaterials is one of the main research directions for demonstrating novel phenomena in NH systems. A typical physical model is a binary array of coupled dielectric resonators with dielectric ceramics as unit cells, which are arranged with alternating coupling distances, materials with different loss and gain, or modification by structural defects.\(^\text{[77]}\)
Recently, the energy band attraction (EBA) caused by the nonorthogonal eigenvectors in NH systems was reported by Wu et al.\(^ {25} \) for the first time. The modified SSH model is shown in Figure 12, and the Hamiltonian could be expressed as follows:

\[
H(K) = [t_a + t_b \cos(ka)] \sigma_x + t_b \sin(ka) \sigma_y + iy\sigma_z
\]  

(11)

where \( a \) is the lattice constant, \( k \) is the Brillouin vector, \( \sigma \) is the Pauli matrix, \( t_a \) and \( t_b \) denote the intradimer and interdimer coupling strengths, respectively, and \( \gamma \) is the NH term, indicating the gain or loss within one dimer.

Then, the energy dispersion of \( E(K) \) could be obtained by Equation (12):

\[
E(K) = \pm \sqrt{t_a^2 + t_b^2 + 2t_a t_b \cos(ka) - \gamma^2}.
\]

(12)

As \( \gamma \) increases, the two-level gapped bands moved closer to each other, then coalesce, and ultimately merge into a flat band that is independent of the Brillouin vector \( k \), possessing PT symmetry, as shown in Figure 13. On
this basis, the authors also observed the topological edge state using this system.

Moreover, the EBA effect in this model was further verified and generalized in a 2D system. For unit cells coupled with different distances, the chiral symmetry was broken, and the band was asymmetric. When the NH parameter was present, a Dirac cone could be achieved, similar to that of graphene. Thus, this study can help understand the framework of the band theory in NH systems and may serve as a viable platform for further promising applications, such as robust light steering, flat band transport without diffraction, and NH hyperbolic metamaterials.

In the artificial nonlinear field, NH systems also have important prospects. Jeon et al.\[26] demonstrated the interplay of a lossy nonlinearity and charge-conjugation (CT) symmetry in the formation of defect modes. They realized an SSH coupled resonator microwave waveguide (CRMW) array with a defect resonator coupled inductively to a PIN diode.

In this model, the SSH chain was established using 17 high-index (n = 6) cylindrical resonators (radius = 4 mm, height = 5 mm) made of a typical microwave dielectric ceramic (ZrSnTiO); the resonant frequency was approximately 6.876 GHz. The intradimer distance was 10 mm (strong coupling, $t_1 = 68$ MHz), and the interdimer distance was 12 mm (weak coupling, $t_2 = 33$ MHz). The central resonator was weakly coupled to both neighbors, and there was a short-circuited diode on the top of the resonator with a Teflon spacer. The
kinked excitation antenna was positioned at the defect resonator, with a top metallic plate supporting the scanning loop antenna. The experimental setup was described mathematically within the framework of mode coupling theory without the consideration of any linear dispersion effects.

The derivation can be found in the original work. when the diode-induced nonlinearity was purely imaginary, the nonlinear defect mode was spectrally protected by the NH CT symmetry. However, with the introduction of high pump powers, the nonlinearity acquired a substantial real part, and a self-induced explicit symmetry violation emerged in the system. Then, the defect mode was no longer protected by the CT symmetry. This can be an extremely desirable feature for various technological applications of topological photonics, from the topological protection of unidirectional defect modes at low incident powers to photonic reflective limiters.

Based on the results above, symmetry breaking often leads to physical innovations. Extending to the field of ceramics with wide in numerous applications, such as ferroelectric, piezoelectric, thermolectric, ferromagnetic, and antiferromagnetic applications, research on ceramic-based dielectric metamaterials in NH systems has just begun. Furthermore, with the introduction of dispersion and polarization loss and gain in ceramics, considerable work remains to be done.

5 | NATURAL CERAMIC MATERIALS INSPIRED BY METAMATERIALS

Before the development of ceramic-based dielectric metamaterials, dielectric ceramics were studied extensively. For most dielectric ceramics, the permittivity, which reflects the ability of the material to respond to an electric field, is positive, which is attributed to the polarization mechanism in different frequency bands. Nowadays, positive permittivity (positive-ε) dielectric ceramics are widely used in various electronic devices and platforms owing to their easily tailored properties.

In dielectric ceramics, permittivity is the macro representation of polarization. In the microwave and terahertz ranges, the permittivity depends on the matching between the frequency of the applied electromagnetic field and the polarization of the ceramic itself, which is mainly attributed to electron displacement polarization and ion displacement polarization. More narrowly, the permittivity arises from the delay in the polarization of molecules (or atoms) in dielectric ceramics from the applied electromagnetic field. This leads to an angular deviation between the instantaneous applied electromagnetic field and the polarized molecular (or atomic) field, resulting in two fields that cannot be synchronized. Then, the polarization is established, and a positive permittivity is obtained. When the applied electromagnetic field is considerably higher than the self-resonant frequency of dielectric ceramics, the delay angle will exceed 180°, and a negative permittivity can be achieved. However, owing to the high intrinsic resonant frequency (starting from the far infrared band) of dielectric ceramics, it was difficult to realize a negative permittivity in the microwave and terahertz bands before the emergence of metamaterials. Using effective medium theory, the intrinsic resonant frequency can be replaced by the resonant frequency of the structure through rational design, which can greatly reduce the resonant frequency. In addition, the above mechanism can be analogously applied to the permeability.

The ceramic-based dielectric metamaterials discussed here are not metamaterials in the true sense, because they do not contain an artificial periodic array. Based on the theory above, natural materials can be modified to exhibit the typical characteristics of metamaterials, such as a near-zero or negative refractive index. Building epsilon-negative (ε′ < 0) or permeability-negative (μ′ < 0) materials is one effective approach for achieving a negative refractive index, which is inevitably required for new microwave equipment and high-power electronic devices, such as microwave absorbers, electromagnetic attenuation, and novel capacitors. Furthermore, when the permittivity or permeability is near zero, a near-zero refractive index can be obtained, which provides near-perfect absorption of electromagnetic waves.

The most common method to fabricate these materials is the introduction of conductive materials into dielectric ceramics. The reaction between the two components should be avoided to ensure the generation of resonance and negative permittivity. For normal resonance in dielectric ceramics, the permittivity can be described by the Lorentz model:

$$\varepsilon_r = 1 + \frac{Nq^2}{m_{\text{eff}}\varepsilon_0} \cdot \frac{1}{\omega_0^2 - \omega^2 + i\omega\tau}.$$ (13)

where \(\omega_0 = 2\pi f_0\) is the characteristic frequency, \(m_{\text{eff}}\) is the effective mass of the carrier, \(N\) is the number of charges per unit volume, \(q\) is the charge of the carrier, \(\omega\) is the angular frequency, and \(\tau\) is the collision frequency. With the introduction of conductive metals, the effective permittivity can be modified, leading to a dilution of the effective electron concentration. Then, the negative permittivity and low-frequency plasma are obtained simultaneously. The Drude model is established under this condition, which can be represented as follows:
\[
\varepsilon_i = 1 - \frac{\omega_p^2}{\omega^2 + \omega_i^2},
\]

(14)

\[
\omega_p = 2\pi f_p = \sqrt{\frac{n_{\text{eff}} e^2}{m_{\text{eff}} \varepsilon_0}},
\]

(15)

Where \(\omega_p\) is the plasma frequency, \(n_{\text{eff}}\) is the effective concentration of conduction electrons, \(\varepsilon_0\) is the vacuum permittivity \((8.85 \times 10^{-12} \text{ F/m})\), \(e\) is the electron charge \((1.6 \times 10^{-19} \text{ C})\).

Initially, porous ceramics were used as the base for negative refractive index materials. Shi et al.\[27\] prepared porous alumina ceramic to match nickel powder, obtaining Ni/Al\(_2\)O\(_3\) composites with negative permittivity and permeability, the preparation process is shown in Figure 14. In this system, the negative permittivity could be illustrated by the Drude model, meanwhile due to the establishment of nickel networks, a large number of current loops would be induced to provide inductance, leading to the negative permeability. Moreover, ceramic-based metamaterials combined with various carbon materials can also exhibit negative permittivity or/and permeability. Due to the plasticity of carbon materials from both structures and characteristics, such as graphene, carbon nanotubes, and carbon nanofibers, porous ceramics are no longer necessary, and the corresponding metamaterials become more diversified.\[106-109\]

Currently, with the development of dielectric ceramics and conductive materials, the focus is no longer just the realization of a near-zero or negative refraction index. Multifunctional integration has gradually become an active area of research, and the compatibility of different dielectric ceramics and conductive materials is the principal aspect. Wang et al.\[110\] reported a type of epsilon-negative material with high thermal conductivity and low electrical conductivity, BaTiO\(_3\)/Cu composites, which were of great importance for high power microwave devices. By modifying the Cu content, a high thermal conductivity of 17.7 W m\(^{-1}\) K\(^{-1}\) and a low electrical conductivity of 0.0022 Ω\(^{-1}\) cm\(^{-1}\) were achieved at 150°C, and perfect absorption performance was obtained near the zero-cross point, demonstrating an effective strategy for realizing thermally conductive and electrically insulating epsilon-negative materials. This conclusion is also applicable to similar systems, such as BaTiO\(_3\)/Ni composites.\[111\]

Another important research direction is the development of ceramics exhibiting both conductive and dielectric properties without metal or carbon. It provides an effective approach for the cofiring and integration of this type of material in applications. Fan et al.\[112\] prepared TiN–Al\(_2\)O\(_3\) composite ceramics for the electromagnetic functionalization of wave shielding or attenuation. They studied the dielectric spectra of the composite ceramics from 10 MHz to 1 GHz, which demonstrated a conversion from insulating to metallic behavior similar to that of dielectric–metal-based systems, achieving negative permittivity. In addition to

![Figure 14 The schematic preparation process of Ni/Al\(_2\)O\(_3\) composites\[27\] Copyright 2020, John Wiley and Sons](image-url)
multiphase systems, single-phase ceramics can also achieve a negative permittivity. Wang et al.\(^{[113]}\) successfully prepared single-phase La\(_{0.5}\)Sr\(_{0.5}\)MnO\(_3\) ceramics by a sol–gel auto-combustion method. They achieved the desired temperature-stable negative permittivity and low dielectric loss from 50 to 600°C. However, owing to the polarization of this material, the performance peaked at approximately 5 MHz. Further study is required to develop single-phase ceramics with negative permittivity at higher frequencies.

6 | OUTLOOK

In this review, we summarize the recent progress on ceramic-based dielectric metamaterials in four representative fields: electromagnetic applications, energy applications, NH systems, and natural materials with a near-zero or negative refraction index. As an important branch of metamaterials, ceramic-based dielectric metamaterials exhibit low dielectric loss, simple structure, excellent multifield tunability, and good environmental adaptability that of great prospects for various applications and new science. From the overview of the latest progress, it is evident that simple all-ceramic metamaterials and versatility have become the predominate direction of development in this area, for higher adaptability and integration in the future applications. Meanwhile, the consequent challenges are gradually spring up.

For example, all-ceramic dielectric metamaterial absorbers would not require a large-area metal backplane in the future. Owing to the stable performance and durability of ceramics in harsh environments, their integration with other devices can be realized, such as radomes and the shell of aircraft. Actually, all-ceramic metamaterial absorbers are theoretically feasible, however, the realization is limited by the design of ceramic systems, and experimental verification is difficult for the strict dimensional requirements of ceramics.\(^{[114]}\) Another example is single-phase natural materials with a negative or near-zero refraction index. For higher frequency bands, it is imperative to develop ceramics with both conductive and dielectric properties from the research of semiconductor ceramics or the construction of unit cells in metamaterials, and determining how to exploit the ceramic system without compromising performance is the key problem to be solved. Moreover, for NH systems, the loss mechanism of dielectric ceramics is relatively clear, and the coupling between loss and gain in the system can be controlled by regulating ceramic loss or other characteristics to obtain more novel physical phenomena.

Thus, on the one side, when focusing on the design of metamaterial structures, more attention should be paid to the tailoring of ceramic compositions for the dispersion and physicochemical properties, to achieve a closed-loop logic chain for different metamaterial constructions. On the other hand, due to the strict limitation of unit cell size and higher frequencies, more advanced processing technologies for ceramics also need to be developed. Then, ceramic-based dielectric metamaterials that can only be realized theoretically before are expected to be materialized, and it also provides a comprehensive system to analyze and promote the development of ceramic-based dielectric metamaterials, which will enable new possibilities in the future.

ACKNOWLEDGEMENTS

This study was supported by Basic Science Center Project of NSFC under grant No. 51788104.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

ORCID

Weijia Luo \(\odot\) http://orcid.org/0000-0002-2609-9980

REFERENCES

[1] Smith DR, Pendry JB, Wiltshire MC. Metamaterials and negative refractive index. Science. 2004;305:788-792.
[2] Liu Y, Zhang X. Metamaterials: a new frontier of science and technology. Chem Soc Rev. 2011;40:2494-2507.
[3] Schurig D, Mock JJ, Justice B, et al. Metamaterial electromagnetic cloak at microwave frequencies. Science. 2006;314:977-980.
[4] Reed EJ, Soljačić M, Joannopoulos JD. Reversed Doppler effect in photonic crystals. Phys Rev Lett. 2003;91:133901.
[5] Pendry JB. Negative refraction makes a perfect lens. Phys Rev Lett. 2000;85:3966-3969.
[6] Choi G, Shahzad F, Bahk YM, et al. Enhanced terahertz shielding of MXenes with nano-metamaterials. Adv Opt Mater. 2018;6:1701076.
[7] Chong Y, Ge L, Cao H, Stone AD. Coherent perfect absorbers: time-reversed lasers. Phys Rev Lett. 2010;105:053901.
[8] Ye KP, Pei WJ, Sa ZH, Chen H, Wu RX. Invisible gateway by superscattering effect of metamaterials. Phys Rev Lett. 2021;126:227403.
[9] Sreekanth KV, Alapan Y, ElKabbash M, et al. Extreme sensitivity biosensing platform based on hyperbolic metamaterials. Nat Mater. 2016;15:621.
[10] Wu Y, Li J, Zhang ZQ, Chan CT. Effective medium theory for magnetodielectric composites: beyond the long-wavelength limit. Phys Rev B: Condens Matter Mater Phys. 2006;74:085111.
[11] Busch K, Soukoulis C. Transport properties of random media: a new effective medium theory. Phys Rev Lett. 1995;75:3442-3445.
[12] Zhao Q, Zhou J, Zhang F, Lippens D. Mie resonance-based dielectric metamaterials. Mater Today. 2009;12:60-69.
[13] Zhao Q, Kang L, Du B, et al. Experimental demonstration of isotropic negative permeability in a three-dimensional dielectric composite. *Phys Rev Lett.* 2008;101:027402.

[14] Wu H, Zhou J, Lan C, Guo Y, Bi K. Long-range magnetic interaction and frustration in double perovskites Sr$_2$NiIrO$_6$ and Sr$_x$ZnIrO$_6$. *Sci Rep.* 2014;4:1.

[15] Yahiaoui R, Némec H, Kuzel P, Kadlec F, Kadlec C, Mounaix P. Tunable THz metamaterials based on an array of paraelectric SrTiO$_3$ rods. *Appl Phys A.* 2011;103:689.

[16] Fu X, Zeng X, Cui TJ, et al. Ultrastructural characterization of the lower motor system in a mouse model of Krabbe disease. *Sci Rep.* 2016;6:1.

[17] Zhang J, Zhai J, Chou X, Shao J, Lu X, Yao X. Microwave and infrared dielectric response of tunable Ba$_{1-x}$Sr$_x$TiO$_3$ ceramics. *Acta Mater.* 2009;57:4491-4499.

[18] Zhang J, Liu W, Zhu Z, Yuan X, Qin S. Strong field enhancement and light-matter interactions with all-dielectric metamaterials based on split bar resonators. *Opt Express.* 2014;22:30889-30898.

[19] Bi K, Wang Q, Xu J, Chen L, Lan C, Lei M. All-dielectric metamaterial fabrication techniques. *Adv Opt Mater.* 2021;9:2001474.

[20] Jahani S, Jacob Z. All-dielectric metamaterials. *Nature Nanotechnol.* 2016;11:23-36.

[21] Yang Y, Kravchenko II, Briggs DP, Valentine J. COP1 E3 ligase protects HYLI to retain microRNA biogenesis. *Nat Commun.* 2014;5:1.

[22] Liu X, Bi K, Li B, Zhao Q, Zhou J. Metamaterial perfect absorber based on artificial dielectric “atoms”. *Opt Express.* 2016;24:20454-20460.

[23] Li L, Wang J, Ma H, et al. Achieving all-dielectric metamaterial band-pass frequency selective surface via high-permittivity ceramics. *Appl Phys Lett.* 2016;108:122902.

[24] Zeng X, Zhang G, Xi X, Li B, Zhou J. Terahertz transmission of square-particle and rod structured TbFeO$_3$ metamaterials. *Mater Lett.* 2019;234:66-68.

[25] Wu M, Peng R, Liu J, Zhao Q, Zhou J. Energy band attraction effect in non-hermitian systems. *Phys Rev Lett.* 2020;125:137703.

[26] Jeon DH, Reisner M, Mortessagne F, Kottos T, Kuhl U. Non-Hermitian CT-symmetric spectral protection of nonlinear defect modes. *Phys Rev Lett.* 2020;125:113901.

[27] Shi ZC, Fan RH, Zhang ZD, et al. Random composites of nickel networks supported by porous alumina toward double negative materials. *Adv Mater.* 2012;24:2349.

[28] Shin D, Kang G, Gupta P, et al. Thermoplasmonic and Photothermal metamaterials for solar energy applications. *Adv Opt Mater.* 2018;6:1800317.

[29] Li Y, Lin C, Zhou D, et al. Scalable all-ceramic nanofilms as highly efficient and thermally stable selective solar absorbers. *Nano Energy.* 2019;64:103947.

[30] Zhou HY, Liu XQ, Zhu XL, Chen XM. Cryptococcal meningitis mimicking cerebral infarction: a case report. *J Am Ceram Soc.* 2018;101:1999-2002.

[31] Zhang B, Li L, Luo W. Oxygen vacancy regulation and its high frequency response mechanism in microwave ceramics. *J Mater Chem C.* 2018;6:11023-11034.

[32] Baranov A, Oh YJ. Microwave frequency dielectric properties of hexagonal perovskites in the Ba$_2$Ta$_2$O$_{15−z}$BaTiO$_3$ system. *J Eur Ceram Soc.* 2005;25:3451-3457.

[33] Levine B. Bond susceptibilities and ionicities in complex crystal structures. *J Chem Phys.* 1973;59:1463-1486.

[34] Hodkinson J, Greenleaves I. Computations of light-scattering and extinction by spheres according to diffraction and geometrical optics, and some comparisons with the Mie theory. *J Opt Soc Am.* 1963;53:577.

[35] Fu Q, Sun W. Mie theory for light scattering by a spherical particle in an absorbing medium. *Appl Opt.* 2001;40:1354.

[36] Kruk S, Kivshar Y. Functional meta-optics and nanophotonics governed by mie resonances. *ACS Photonics.* 2017;4:2638-2649.

[37] Wheeler MS, Atchison JS, Mojabedi M. Coupled magnetic dipole resonances in sub-wavelength dielectric particle clusters. *J Opt Soc Am B.* 2010;27:1083.

[38] Bohren CF, Huffman DR. *Absorption and scattering of light by small particles.* John Wiley & Sons; 2008.

[39] Lewin L. The electrical constants of a material loaded with spherical particles. *J Instit Electr Eng Part III Radio Commun Eng.* 1947;94:65.

[40] Liu X, Lan C, Bi K, Li B, Zhao Q, Zhou J. Dual band metamaterial perfect absorber based on Mie resonances. *Appl Phys Lett.* 2016;109:062902.

[41] Liu X, Lan C, Li B, Zhao Q, Zhou J. Ultrastructural characterization of the lower motor system in a mouse model of Krabbe disease. *Sci Rep.* 2016;6:1.

[42] Xu Y, Liu T, He Y, Yuan X. Dielectric properties of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-$\text{La(B}_0.5\text{Ti}_0.5$O$_3$ (B=Mg, Zn) ceramics. *IEEE Trans Ultrason Eng.* 2009;56:2343-2349.

[43] Bi K, Zhu W, Lei M, Zhou J. Magnetically tunable wideband microwave filter using ferrite-based metamaterials. *Appl Phys Lett.* 2015;106:173507.

[44] Bi K, Guo Y, Liu X, et al. Magnetically tunable mie resonance-based dielectric metamaterials. *Sci Rep.* 2014;4:7001.

[45] Luo W, Li L, Yu S, et al. Bond theory, terahertz spectra, and dielectric studies in donor-acceptor (Nb–Al) substituted ZnTiNb$_2$O$_6$ system. *J Am Ceram Soc.* 2019;102:4612-4620.

[46] Gao J, Lan C, Zhao Q, Li B, Zhou J. Experimental realization of Mie-resonance terahertz absorber by self-assembly method. *Opt Express.* 2018;26:13001.

[47] Belov V, Belov I, Harel L. Preparation of spherical Yttria-stabilized zirconia powders by reactive-spray atomization. *J Am Ceram Soc.* 1997;80:982-990.

[48] Watanabe M, Kuroda S, Yamawaki H, Shiwa M. Terahertz dielectric properties of plasma-sprayed thermal-barrier coatings. *Surf Coat Technol.* 2011;205:4620-4626.

[49] Bi K, Yang D, Chen J, et al. Experimental demonstration of ultra-large-scale terahertz all-dielectric metamaterials. *Photonics Res.* 2019;7:457.

[50] Fan JA, Bao K, Sun L, et al. Plasmonic mode engineering with templated self-assembled nanoclusters. *Nano Lett.* 2012;12:5318-5324.

[51] Zeng X, Wang R, Xi X, Li B, Zhou J. 3D direct writing of terahertz metamaterials based on TbFeO$_3$ dielectric ceramics. *Appl Phys Lett.* 2018;113:081901.
[52] Li Y, Lin C, Wu Z, et al. Solution-processed all-ceramic plasmonic metamaterials for efficient solar–thermal conversion over 100–727°C. Adv Mater. 2021;33:2005074.

[53] Boltasseva A, Atwater HA. Low-loss plasmonic metamaterials. Science. 2011;331:290-291.

[54] Yao K, Liu Y. Plasmonic metamaterials. Nanotechnol Rev. 2014;3:177-210.

[55] Cheng F, Gao J, Stan L, Rosenmann D, Czaplewski D, Yang X. Aluminum plasmonic metamaterials for structural color printing. Opt Express. 2015;23:14552-14560.

[56] Pu M, Ma X, Li X, Guo Y, Luo X. Merging plasmonics and metamatamaterials by two-dimensional subwavelength structures. J Mater Chem C. 2017;5:4361-4378.

[57] Paldi RL, Wang X, Sun X, et al. Vertically aligned Ag₆Au₁ₓ alloyed nanopillars embedded in ZnO as nanoengineered low-loss hybrid plasmonic metamaterials. Nano Lett. 2020;20:3778-3785.

[58] Chang CC, Kort-Kamp WI, Nogan J, et al. High-temperature refractory metasurfaces for solar thermophotovoltaic energy harvesting. Nano Lett. 2018;18:7665-7673.

[59] Zhou L, Tan Y, Ji D, et al. Self-assembly of highly efficient, broadband plasmonic absorbers for solar steam generation. Sci Adv. 2016;2:e1501227.

[60] Li W, Guler U, Kinsey N, et al. Refractory plasmonics with titanium nitride: broadband metamaterial absorber. Adv Mater. 2014;26:7959-7965.

[61] Weinstein LA, Loomis J, Bhatia B, Bierman DM, Wang EN, Chen G. Concentrating solar power. Chem Rev. 2015;115:12797-12838.

[62] Liu Y, Lu C, Zhang P, Yu J, Zhang Y, Sun ZM. Mechanisms behind the spontaneous growth of Ti whiskers on the Ti₃SnC ceramics. Acta Mater. 2020;185:433-440.

[63] Kaur M, Ishii S, Shinde SL, Nagao T. All-ceramic microfibrous solar steam generator: tin plasmonic nanoparticle-loaded transparent microfibers. ACS Sustain Chem Eng. 2017;5:8523-8528.

[64] Wang J, Ren Z, Luo Y, et al. Radially aligned porous silk fibroin scaffolds as functional templates for engineering human biomimetic hepatic lobules. ACS Appl Mater Interfaces. 2021:2101229.

[65] Zhao J, Yang Y, Yang C, et al. A hydrophobic surface enabled salt-blocking 2D Ti₃C₂ MXene membrane for efficient and stable solar desalination. J Mater Chem A. 2018;6:16196-16204.

[66] Sani E, Meucci M, Mercatelli L, et al. Titanium diboride ceramics for solar thermal absorbers. Sol Energy Mater Sol Cells. 2017;169:313-319.

[67] Hadad Y, Vitelli V, Alu A. Solitons and propagating domain-walls in topological resonator arrays. ACS Photonics. 2017;4:1974-1979.

[68] Lumer Y, Plotnik Y, Rechtsman MC, Segev M. Self-localized states in photonic topological insulators. Phys Rev Lett. 2013;111:243905.

[69] Leykam D, Chong YD. Edge solitons in nonlinear photonic topological insulators. Phys Rev Lett. 2016;117:143901.

[70] Wang Y, Lang L-J, Lee CH, Zhang B, Chong Y. Double-slit photoelectron interference in strong-field ionization of the neon dimer. Nat Commun. 2019;10:1.

[71] Zhou X, Wang Y, Leykam D, Chong YD. Optical isolation with nonlinear topological photonics. New J Phys. 2017;19:095002.

[72] Malzard S, Cancellieri E, Schomerus H. Topological dynamics and excitations in lasers and condensates with saturable gain or loss. Opt Express. 2018;26:22506-22518.

[73] Hadad Y, Khanikaev AB, Alu A. Self-induced topological transitions and edge states supported by nonlinear staggered potentials. Phys Rev B: Condens Matter Mater Phys. 2016;93:155112.

[74] Hadad Y, Soric JC, Khanikaev AB, Alu A. Self-induced topological protection in nonlinear circuit arrays. Nat Electron. 2018;1:178-182.

[75] Dobrykh D, Yulin A, Slobozhanynuk A, Poddubny A, Kivshar YS. Nonlinear control of electromagnetic topological edge states. Phys Rev Lett. 2018;121:163901.

[76] Yang M, Ye Z, Farhat M, Chen P-Y. Pipeline safety early warning by multifluorescence-FUSION and lightGBM analysis of signals from distributed optical fiber sensors. IEEE Trans Instrum Meas. 2021;70:1-13.

[77] Poli C, Bellec M, Kuhl U, Mortessagne F, Schomerus H. Selective enhancement of topologically induced interface states in a dielectric resonator chain. Nat Commun. 2015;6:1.

[78] Gorlach MA, Ni X, Smirnova DA, et al. Far-field probing of leaky topological states in all-dielectric metasurfaces. Nat Commun. 2018;9:1.

[79] Bisson J-F, Nonguiera YC. Single-mode lasers using parity-time-symmetric polarization eigenstates. Phys Rev A. 2020;102:043522.

[80] Su WP, Schrieffer J, Heeger AJ. Solitons in polyacetylene. Phys Rev Lett. 1979;42:1698-1701.

[81] Poddubny A, Irsho I, Belov P, Kivshar Y. Hyperbolic metamaterials. Nat Photonics. 2013;7:948-957.

[82] Hou J, Li Z, Luo X-W, Gu Q, Zhang C. Topological bands and triply degenerate points in non-Hermitian hyperbolic metamaterials. Phys Rev Lett. 2020;124:073603.

[83] Biesenthal T, Kremer M, Heinrich M, Sramek A. Experimental realization of PT-symmetric flat bands. Phys Rev Lett. 2019;123:183601.

[84] Zhao H, Qiao X, Wu T, Midya B, Longhi S, Feng L. Non-Hermitian topological light steering. Science. 2019;365:1163-1166.

[85] Reaney IM, Iddles D. Microwave dielectric ceramics for resonators and filters in mobile phone networks. J Am Ceram Soc. 2006;89:2063-2072.

[86] Kagata H, Inoue T, Kato J, Kameyama I. Low-fire bismuth-based dielectric ceramics for microwave use. Jpn J Appl Phys. 1992;31:3152-3155.

[87] Hennings D, Schreinemacher B, Schreinemacher H. High-permittivity dielectric ceramics with high endurance. J Eur Ceram Soc. 1994;13:81-88.

[88] Huan TD, Boggs S, Teyssedre G, et al. Advanced polymeric dielectrics for high energy density applications. Prog Mater Sci. 2016;63:236-269.

[89] Yao Z, Song Z, Hao H, et al. Homogeneous/inhomogeneous-structured dielectrics and their energy-storage performances. Adv Mater. 2017;29:1601727.

[90] Yang L, Kong X, Li F, et al. Perovskite lead-free dielectrics for energy storage applications. Prog Mater Sci. 2019;102:72-108.
[91] Wang Z, Fu X, Zhang Z, et al. Paper-based metasurface: turning waste-paper into a solution for electromagnetic pollution. *J Clean Prod*. 2019;234:588-596.

[92] Zheludev NI, Kvivshar YS. From metamaterials to metadevices. *Nat Mater*. 2012;11:917-924.

[93] Zakri T, Laurent J-P, Vauclin M. Theoretical evidence for 'Lichtenecker's mixture formulae' based on the effective medium theory. *J Phys D: Appl Phys*. 1998;31:1589-1594.

[94] Koschny T, Kafesaki M, Economou E, Soukoulis C. Effective medium theory of left-handed materials. *Phys Rev Lett*. 2004;93:107402.

[95] Slovick BA, Yu ZG, Krishnamurthy S. Generalized effective-medium theory for metamaterials. *Phys Rev B: Condens Matter Mater Phys*. 2014;89:155118.

[96] Shi Z, Wang J, Mao F, Yang C, Zhang C, Fan R. Significantly improved dielectric performances of sandwich-structured polymer composites induced by alternating positive-k and negative-k layers. *J Mater Chem A*. 2017;5:14575-14582.

[97] Zhao B, Yao W, Niu Q. Valley-degenerate topological insulator transition in SmBaCo2O6 single crystal. *Phys Rev B*. 2017;95:195103.

[98] Fan G, Zhao Y, Xin J, et al. Negative permittivity in titanium nitride-alumina composite for functionalized structural ceramics. *J Am Ceram Soc*. 2020;103:403-411.

[99] Wang Z, Sun K, Xie P, et al. Design and analysis of negative permittivity behaviors in barium titanate/nickel metamaterials. *Acta Mater*. 2020;185:412-419.

[100] Luo W, Yan S, Zhou J. Theoretical evidence for the presence of negative permittivity in random carbon nanotubes/alumina nanocomposites. *Nanoscale*. 2017;9:5779-5787.

[101] Xie P, Wang Z, Zhang Z, et al. Silica microsphere templated self-assembly of a three-dimensional carbon network with stable radio-frequency negative permittivity and low dielectric loss. *J Mater Chem C*. 2018;6:5239-5249.

[102] Cheng C, Fan R, Wang Z, et al. Radio-frequency negative permittivity in the graphene/silicon nitride composites prepared by spark plasma sintering. *J Am Ceram Soc*. 2018;101:1598-1606.

[103] Wang Z, Sun K, Xie P, et al. Epsilon-negative BaTiO3/Cu composites with high thermal conductivity and yet low electrical conductivity. *J of Materiomics*. 2020;6:145-151.

[104] Wang Z, Sun K, Xie P, et al. Fabrication of graphene network in metal crystal of ordered double perovskite Sr2FeMoO6. *J Phys Soc Jpn*. 2020;89:056625.

[105] Jiang Z, Wang J, Mao F, Chen S, Wang X. Bilayer polymer metamaterials containing negative permittivity layer for new high-k materials. *ACS Appl Mater Inter*. 2017;9:1793-1800.

[106] Biskup W, Czapla K. Perfect magnetic shielding properties of conductive poly(vinylidene fluoride)/Ni chain composite films with negative permittivity. *J Mater Chem C*. 2017;5:6954-6961.

[107] Wang J, Shi Z, Mao F, Chen S, Wang X. High frequency negative permittivity from Fe/Al2O3 composites with high metal contents. *J Am Ceram Soc*. 2012;95:67-70.

[108] Fyodorov YV, Sommers H-J. Statistics of resonance poles, phase shifts and time delays in quantum chaotic scattering: random matrix approach for systems with broken time-reversal invariance. *J Math Phys*. 1997;38:1918-1981.

[109] Mostafazadeh A. Pseudo-Hermiticity versus PT symmetry: the necessary condition for the reality of the spectrum of a non-Hermitian Hamiltonian. *J Math Phys*. 2002;43:205-214.

[110] Mostafazadeh A. Pseudo-Hermiticity versus PT-symmetry. II. A complete characterization of non-Hermitian Hamiltonians with a real spectrum. *J Math Phys*. 2002;43:2814.

[111] Mostafazadeh A. Pseudo-Hermiticity versus PT-symmetry III: equivalence of pseudo-Hermiticity and the presence of antilinear symmetries. *J Math Phys*. 2002;43:3944-3951.

[112] Bender CM. Making sense of non-Hermitian Hamiltonians. *Rep Prog Phys*. 2007;70:947-1018.