

Perspective

Thermal Metamaterial: Fundamental, Application, and Outlook

Jun Wang,¹ Gaole Dai,² and Jiping Huang^{1,*}

SUMMARY

Thermal metamaterials have amazing properties in heat transfer beyond naturally occurring materials owing to their well-designed artificial structures. The idea of thermal metamaterial has completely subverted the design of thermal functional devices and makes it possible to manipulate heat flow at will. In this perspective, we review the up-to-date progress of thermal metamaterials starting from 2008. We focus on both the key theoretical fundamentals and techniques for applications and give a perspective of scale-based classification on thermal metamaterials' theories and applications. We also discuss the junction between macroscale and microscale design methods and propose some prospects for the future trend of this field.

INTRODUCTION

Heat energy is widely present in our daily life. Most high-grade energy will eventually be released to the environment in the form of heat. Thus, how to manipulate heat at will has not only scientific significance but also practical application value. Generally speaking, thermal phenomena can usually be passively described by the four famous laws of thermodynamics. It is hard to control them actively because the thermal properties of naturally occurring materials are fixed. However, with the booming developments of thermal metamaterials starting from 2008, this challenge has been overcome. By well-designed artificial structures instead of natural materials' intrinsic properties, heat transfer can approximately be manipulated arbitrarily. Thus, many fascinating phenomena and devices have been theoretically predicted and experimentally achieved (Huang, 2020).

First, let us glance at the history of metamaterials for a sketchy profile (Wegener, 2013; Kadic et al., 2013; Huang, 2020); see Figure 1. Metamaterials originated from wave systems. It is known that the refractive index of electromagnetic (EM) waves is usually positive, which means positive permittivity and permeability are requested. In the 1960s, Veselago challenged this common sense and proposed the assumption of simultaneous negative permittivity and permeability, which may lead to a series of anomalous EM wave transfer phenomena (Veselago, 1968). However, the Russian physicist's idea did not call for attention until 1990s, when Pendry and collaborators successfully experimentally obtained effective negative permittivity and permeability in the microwave band with metal rods periodic arrays (Pendry et al., 1996) and split-ring resonators (Pendry et al., 1999). Since then, the field of metamaterial physics has grown vigorously. In 2006, Pendry et al. developed a mathematical tool for designing metamaterials, which is called transformation optics, and proposed the famous concept of invisibility cloak (Pendry et al., 2006). The cloak just relies on negative permittivity and permeability. Another significant work in wave systems was reported by Sheng's group (Liu et al., 2000). Sheng led the invention of locally resonant sonic materials that initiated the field of acoustic metamaterials. Their work directly inspired the subsequent metamaterial researches beyond EM wave systems, including those in acoustics, elasticity, or mechanics. On the other hand, the concept of transformation optics was expanded from wave systems to diffusion systems by Fan et al. and Chen et al. successively in 2008 (Fan et al., 2008; Chen et al., 2008), which aroused the subsequent enormous research of thermal metamaterials. This is the acknowledged origin of thermal metamaterials in the literature (Narayana and Sato, 2012; Ball, 2012; Maldovan, 2013a).

To date, the fundamental theories of thermal metamaterials can be classified into two categories: macroscopic phenomenological theory and microscopic phononic/thermal photonic theory. The former contains transformation thermotics and its extended theories, whereas the latter is related with phononics and photonics. Accordingly, the applications of thermal metamaterials are developed in macroscopic and

¹Department of Physics, State Key Laboratory of Surface Physics, and Key Laboratory of Micro and Nano Photonic Structures (MOE), Fudan University, Shanghai 200438, China

²School of Sciences, Nantong University, Nantong 226019, China

*Correspondence: jphuang@fudan.edu.cn
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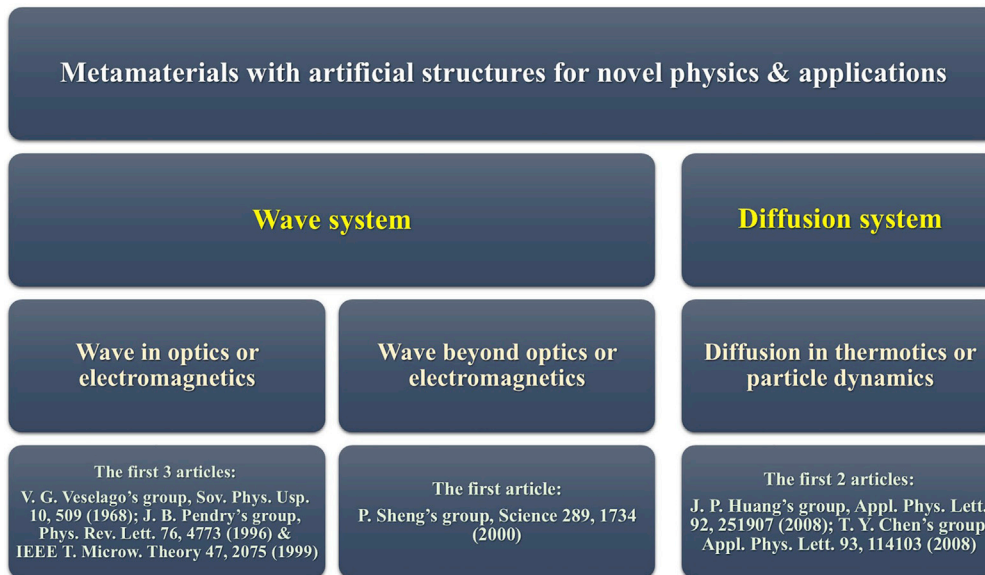


Figure 1. Sketchy Profile of the Origin of Metamaterials in Different Physical Systems

The physical systems are divided into wave and diffusion systems. Thermal metamaterial is initial and main branch in diffusion systems. Image adapted from [Huang \(2020\)](#).

microscopic ways, respectively. In this perspective, we review the existing fundamentals and applications of thermal metamaterials. A brief outlook in this field is given in the end.

FUNDAMENTAL

Macroscopic Phenomenological Theory

The great success of transformation optics ([Pendry et al., 2006](#)) in controlling electromagnetic fields inspired its analogs in other fields. The timeline of development of macroscopic phenomenological theory is illustrated in [Figure 2](#), which originated directly from Pendry et al.'s works. In 2008, Fan et al. extended the transformation method to the steady heat conduction domain ([Fan et al., 2008](#)). Although diffusion systems and wave systems follow divergent governing equations, Fan et al. theoretically proved that form-invariance of diffusion equations kept under spatial coordinate transformation. Transformation thermotics was accordingly proposed for manipulating diffusive thermal fields. By elaborately tailoring the spatial thermal conductivities predicted by the transformation theory, heat flow can be guided at will. They designed a thermal cloak as an original application prototype of transformation thermotics, which can protect central cloaking regions from heat flow without disturbing external fields. Soon, Chen et al. applied the transformation theory in anisotropic background mediums ([Chen et al., 2008](#)). Transformation thermotics was then proved valid in arbitrary backgrounds, whether they are isotropic or anisotropic. The above two pioneering works started up the study of manipulating heat flow by using artificial structures. But they are confined to steady states, namely, the temperature distribution of the whole system is independent of time. However, the process of heat conduction is usually transient, evolving from unsteady to steady states with time. Guenneau et al. studied a transient case with the source and rate-of-time terms in heat conduction equations and deduced a completed set of transformation rules for treating both steady and transient cases ([Guenneau et al., 2012](#)). Soon after, the first experimental validation was executed by Narayana et al. ([Narayana and Sato, 2012](#)). They utilized multi-layer isotropic shell structures to imitate the anisotropic parameters of naturally inexistent materials predicted by transformation thermotics. Then, transient cases were also demonstrated experimentally ([Narayana et al., 2013](#); [Schittny et al., 2013](#)). Since then, the research of thermal metamaterials ([Maldovan, 2013a](#)) has set off an unprecedented boom in both fundamental theories and practical applications.

For handling nonlinear heat conduction, say, thermal conductivities were temperature dependent, Li et al. built nonlinear transformation thermotics ([Li et al., 2015](#)). On the basis of it, the concept of intelligence or self-adaption was introduced into thermal metamaterials. This work paved a way for applying

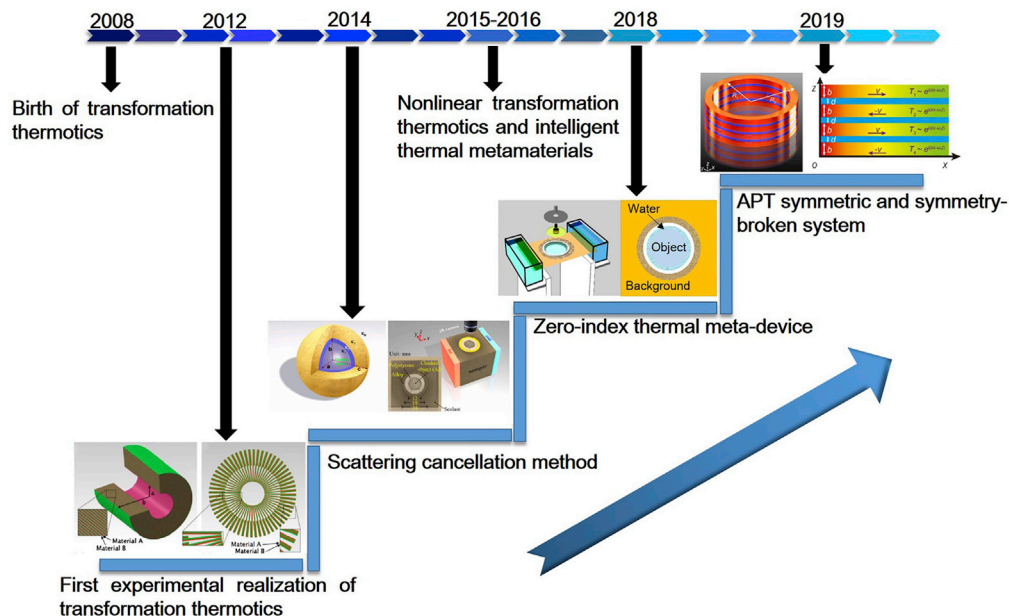


Figure 2. Timeline of Macroscopic Phenomenological Theory Development in Thermal Metamaterials

Image reproduced with permission from Narayana et al. (2012) Narayana and Sato, 2012, Han et al. (2014a, 2014b), and Cao et al. (2020). Copyright 2012 American Physical Society, 2014 American Physical Society, and 2020 Engineered Science Publisher LLC.

transformation thermotics beyond linear heat conduction. Recently, besides conduction realm, the transformation theory was extended to thermal convective systems by Dai et al. (Dai et al., 2018; Dai and Huang, 2018) and Rossland thermal radiative systems by Xu et al. (Xu et al., 2020a). In fact, convection or radiation can be regarded as a sort of nonlinear heat transfer mode because both convective and radiative flows contain explicit nonlinear terms (say, flows are not proportional to temperature gradients). From this point of view, nonlinear transformation thermotics is of essential significance for modulating complex heat transfer beyond linear conduction. More recently, Xu et al. synthesized three main modes of heat transfer and gave a framework of transformation omnithermotics (Xu et al., 2020b). This work provides a systematic summary of manipulating three basic modes of heat transport simultaneously.

The spatial distribution of thermal conductivity predicted by transformation thermotics is usually anisotropic, inhomogeneous, and with singular values at some spatial points. This is because of the underlying mathematical requirement of thermal conductivity transformation from virtual space to real space. However, this will limit the fabrication of practical devices. Inspired by the scattering cancellation method, which was first employed in cloaking static magnetic fields, Han et al. (2014a) and Xu et al. (2014) proposed a bilayer cloaking scheme. This is a direct result of solving the Laplacian equation with particular boundary constraints for heat conduction. Instead of complicated thermal conductivities required by the transformation theory, a bilayer cloak only needs two concentric alternate shells with isotropic natural materials. The inner layer approximates zero thermal conductivity in order to prevent heat flow from running into cloaking regions, whereas the outer layer has a specific thermal conductivity for rectifying external thermal fields. This method applies to almost all cases including two- or three-dimensional designs and steady or transient situations. Recently, the bilayer scheme was not limited to conduction. Thermal convective and radiative terms were taken into consideration in governing equations. Multithermal (Yang et al., 2019) or even omnithermal (Yang et al., 2020) bilayer schemes were proposed for cloaking or focusing multiple heat transport modes simultaneously.

With the rapid development of manipulation methods, researchers are dissatisfied with realizing only single function or controlling only single physical field. The first attempt of controlling multi-physics fields on one device was executed by Li et al. (2010). They discussed thermal and electrical conductivities of cloaking shells by effective medium approximation (Huang and Yu, 2006) and theoretically proposed a bifield single-functional transformation-based cloak. Another bifield bifunctional device was designed by Moccia et al.

(2014). They proposed a simultaneous electrical-cloak and thermal-concentrator device with different transformation operations on electrical and thermal conductivities. These two theoretical works were established on the fact that heat and electric current transport equations keep form consistency under the coordinate transformation and different fields are uncoupled (say, currents transport independently). Owing to the difficulty of transformation parameter realization in multi fields, the first experiment of multi-physics cloak was resorted to the scattering cancellation method (Ma et al., 2014). This work laid a solid foundation for subsequent research. It should be noticed that the above works are restricted to uncoupled fields, namely, thermal and electrical flows do not affect each other. However, the coupled fields will be more complicated for manipulation. Stedman et al. studied the coupled transport of heat and electric flows for the first time (Stedman and Woods, 2017). The transformation rule was thus developed for considering coupling coefficients due to Seebeck or Peltier effects. They also put forward a feasible experimental scheme by multilayer composites, which was verified by simulation results. In 2019, Wang et al. proposed a bilayer design for controlling coupled thermoelectric fields (Wang et al., 2019). In fact, thermal convection can be treated as a bifield process of heat and mass transfer. So devices designed by the transformation thermal convection method can manipulate heat and flow velocity at the same time (Dai et al., 2018; Dai and Huang, 2018). The research of multi-physics multi-function metamaterials has profound significance because one can utilize single field to control other fields on such device. So multi-field control methods may be expected for future practical applications.

As we know, transformation theory and other extended methods are usually applied on thermal conduction first and then on convection and radiation with the same device designs like cloaks, concentrators, and rotators. However, some different devices can be designed in convection and radiation whose functions cannot be easily realized in conductive systems. Some recent works based on convection-conduction systems has shown a potential route to explore unprecedented functional devices through convective nature. For example, a distinct bilayer cloak was realized in an experiment whose inner layer is running water circulating around the core (Li et al., 2019a). In that way, the convection of water can induce an infinite effective thermal conductivity, which can be seen as an analogy of zero-index in optics. In fact, higher efficiency of heat transfer in convection has inspired some important devices including heat pipes and vapor chambers in heat management. Soon after, another convection-conduction system was found to be a nice tool to study anti-parity-time symmetry phase change using non-Hermitian dynamics. The phenomenon of anti-parity-time symmetry breaking phase transition was predicted and first observed in diffusive processes (Li et al., 2019b; Cao et al., 2020). The convective part in heat transfer comes from two coupled solid rings circling in opposite directions and the speed of rings can determine whether the system is in the phase of anti-parity-time symmetry. This system can not only be an ideal platform for studying diffusion-system non-Hermitian dynamics but also have potential applications in controlling heat and mass transfer. With the help of convection-conduction systems, the classical effective medium theory has been generalized from predicting static systems to predicting dynamic ones. Li et al. derived that effective thermal conductivity of such systems with both static and moving parts can be described in a complex plane (, 2020b) and thus may lead to many wave-like functionalities. Xu et al. pointed out that the real and imaginary parts of complex thermal conductivities were corresponding to thermal conduction and convection. Thus, unique features in wave systems can be transferred to thermal conduction-convection systems by the introduced gain and loss. They successively proposed many counterparts of wave systems in thermal conduction-convection systems such as transformation complex thermotics (Xu and Huang, 2020c), negative thermal transport (Xu and Huang, 2020d), and thermal convection-diffusion crystal (Xu and Huang, 2020e) for modulating wave-like temperature profiles. It is expectable that more exciting phenomena can be predicted in thermotics with thermal conduction-convection systems. But the experimental realization and available devices are still facing challenges.

Essentially, the metamaterial design is an inverse problem, in which we preset the eventual functionality and search for the realization scheme. As we can see above, the transformation theory and scattering cancellation method give analytical solutions for some inverse problems. A more traditional way to solve inverse problems is numerical optimization, including size optimization, shape optimization, and topology optimization. The computational optimization was first employed for guiding experimental design of heat flux shielding, focusing, and reversal (Dede et al., 2014). Later, some researchers in industry used the gradient-based algorithm to design multilayer structures on the printed circuit board (PCB) (Dede et al., 2015) with high efficiency in heat management. Then, benefiting from the development of computer science, black-box optimizations like particle swarm optimization-based algorithms (Alekseev and Tereshko,

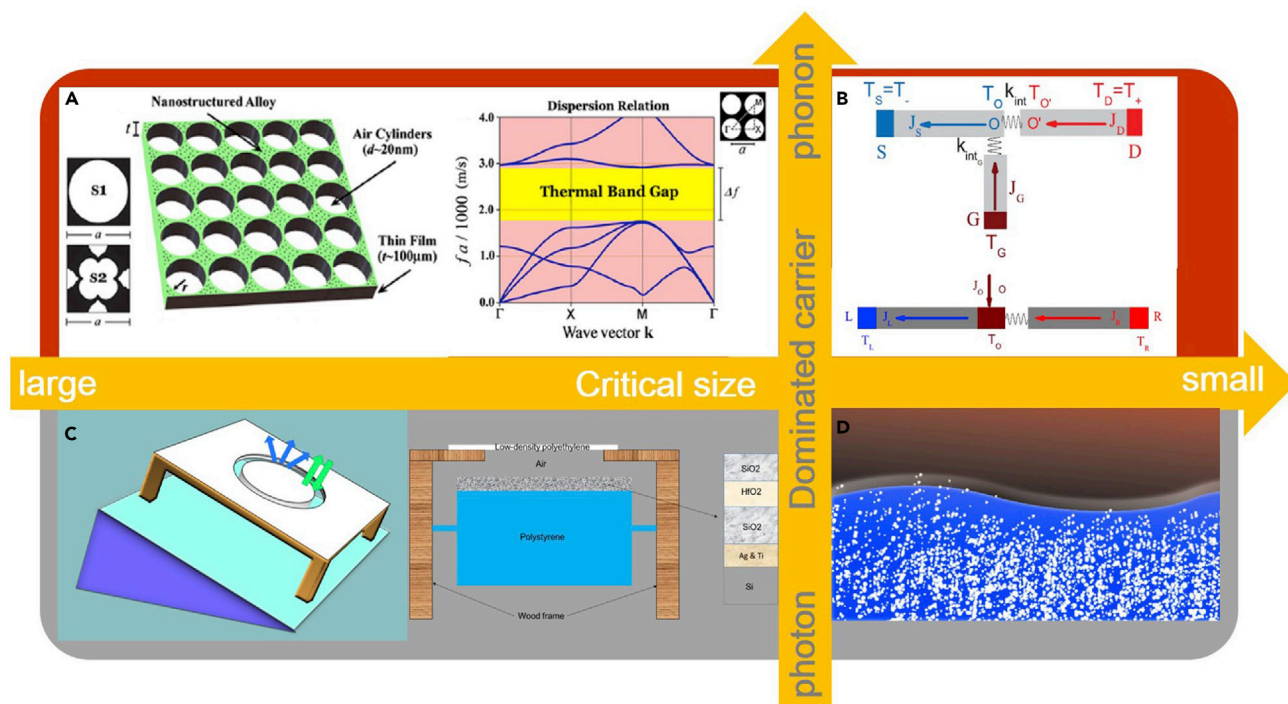


Figure 3. Schematic Diagram of Microscopic Phononic/Thermal Photonic Theory

The horizontal axis represents the magnitude of artificial structures' critical sizes, whereas the vertical axis indicates the classification of dominated carriers. (A) Thermocrystal structure and band gap spectrum. Image reproduced with permission from [Maldovan \(2013b\)](#). Copyright 2013 American Physical Society. (B) Configurations of the phononic transistor (upper panel) and phononic memory (lower panel) devices. Image reproduced with permission from [Wang and Li, 2007](#). Copyright 2007 American Physical Society. (C) Schematic diagram of photonic radiative cooler setup and its functional film's details. (D) Schematic diagram of glass-polymer hybrid thin film microstructure.

2019) and CMA-ES (covariance matrix adaptation evolution strategy) ([Fujii et al., 2018](#)) were used in designing thermal metamaterials mainly for thermal conduction. Recently, multi-physics and multi-functionality devices were also refreshed by topology optimization ([Fujii and Akimoto, 2019, 2020](#)). We expect the optimization methods can be used for cases when the governing equations do not meet the requirement of transformation theory or multiple objects should be realized for thermal modulation. Also, isotropy and homogeneousness on materials are usually requested in numerical optimizations that can simplify the requirements for experimental materials.

Microscopic Phononic/Thermal Photonic Theory

The macroscopic phenomenological theory has been extended to microscale recently ([Hu and Luo, 2019](#)). For example, [Choe et al.](#) demonstrated a monolithic platform with the ion-writing process to achieve arbitrary thermal metamaterial patterns ([Choe et al., 2019](#)). However, this does not touch the nature of heat transport in microscale. On the microscopic level, the dominant heat carriers are phonons for semiconductors and insulators. As acoustic phonons have been successfully modulated by phononic crystals, it is natural to ask how to control thermal phenomena using phononic crystals or more specifically, thermal crystals. At room temperatures or higher ones, heat transfer is mainly influenced by high-frequency phonons whose wave lengths are small and thus shall behave more like particles than waves. So, the key point here is how to restrict the heat phonons at low frequencies and take them as elastic waves if we want to use crystal structures to modulate heat transfer. [Maldovan \(2013b\)](#) proposed a model called thermocrystal using the Si-Ge alloy with nanoparticles embedded in a thin film. This structure can block the transport of high-frequency phonons by bulk scattering and extreme-low-frequency phonons by boundary scattering and then gets a narrow spectrum at a hypersonic range within the room temperature, as shown in [Figure 3A](#). This spectrum can match the band gap generated by placing periodic air holes in the thin film (periodicity~20 nm) and can have potential applications in guiding heat phonons or heat conduction like waves. However, later

experimental works on such Bragg-type crystals showed that it was still difficult to exhibit wave nature of thermal phonons in periodic structures as the particle or diffusive nature can be dominant when the temperature is above 10 K in common materials (Zen et al., 2014; Wagner et al., 2019; Lee et al., 2017; Maire et al., 2017). So there remains a long way to go for realistic thermocrystals. A recent work developed this artificial periodic structure and proposed a multiple-lattice-constant supercrystal structure (Xu and Jiang, 2020). But it still needs further experimental verifications. On the other hand, another crystal structure based on local resonance (rather than Bragg scattering) can also be used to generate hybrid band gap at low frequencies for heat transfer at room temperatures (Davis and Hussein, 2014). It was named as a nanophononic metamaterial because its size is much smaller than previous acoustic metamaterials. Usually, the band gap can reduce the thermal conductivity of the material and thus can benefit the thermoelectric efficiency. Some recent works about using these two kinds of phononic crystals and their comparison were reported (Sledzinska et al., 2020; Hussein et al., 2020). Besides the Bragg-type crystal and locally resonant crystal, recently, aperiodic superlattices or random multilayer structures were also found effective systems for tuning the wave nature of phonons (Chakraborty et al., 2020; Hu et al., 2020). For example, thermal conductivity can be significantly reduced in GaAs/AlAs superlattices with clean interfaces (Hu et al., 2020). Resorting to machine learning or other optimization methods, some unusual cognitions on structures of superlattices impacting heat transport may arise.

Different from transferring the concept of acoustic phononic crystal to thermocrystal, another point of view to manipulate phonons came from controlling electrons or photons on micro devices. Early to 2004, Bao-wen Li and his collaborators led the research of phononic information processing. Like carriers of heat transport, phonons can not only carry heat energy but also transfer information. By modulating lattice vibrations with designed structures, which is usually described by phononic modes, many phononic calculation elements such as thermal diodes (Li et al., 2004), thermal logical gates (Wang and Li, 2007), and thermal memories (Wang and Li, 2008) were proposed. These phononics-based elements can be regarded as counterparts of electric devices; see Figure 3B. In principle, both nonlinearity in thermal conductivity and asymmetry in geometric construction serve as two key factors in realizing phononic calculation devices. A question is how to combine the phononic elements with traditional electronic elements in existing electrical calculation devices, or even replace them. The speed, accuracy, and efficiency on operating phonons in micro-device need to be further improved for future applications.

Besides phononic engineering, the thermal photonic method is another important way to tailor radiative heat transport, both in far fields and near fields. Let us recall a mature concept of radiative cooling, which means reducing objects' temperature by thermal radiation between objects and outer space. Before 2014, this process could only work at night, whereas Raman et al. reported a well-tailored structure that could achieve radiative cooling in both daytime and night (Raman et al., 2014). The photonic design enabled high emissivities at the atmospheric window and low absorptivities at the solar spectrum, as illustrated in Figure 3C. So, the received energy from the sun in daytime was controlled to a lower level, compared with the emissive energy. Although the principle was readily understood, the experimental result was encouraging that about 4.9°C reduction of temperature was achieved compared with ambient temperatures. Since then, different structures of composite films have been proposed to raise the efficiency of daytime radiative cooling and reduce manufacturing difficulties. Figure 3D displays a glass-polymer hybrid thin film microstructure, which may facilitate the quantity production (Zhai et al., 2017). Particularly, biologically inspired photonic films were also reported successively. The efficient radiative-cooling photonic crystal structures of Saharan silver ants (Shi et al., 2015) or Neocerambyx gigas (Zhang et al., 2020) were imitated to design such specific photonic films. These ideas enriched the design schemes of thermal photonics. It is noted that the radiative cooling process is not limited to single heat transfer mode. Thermal conduction and convection also play roles on cooling effects. With the deeper combination of thermal metamaterials and photonic structures, more booming developments will be promisingly achieved in this field.

APPLICATION

Macroscopic Application

Based on transformation thermotics, functional thermal devices such as cloaks, concentrators, and rotators were designed. They are expected to play important roles in heat management. For example, a heat signature transformation scheme was proposed for achieving thermal illusion by Hu et al. (2018b). They manipulate the interior heat source into divergent illusions in size, position, and quantity while maintaining the exterior heat profiles with the transformation method. Later, Hu et al. applied the regionalization

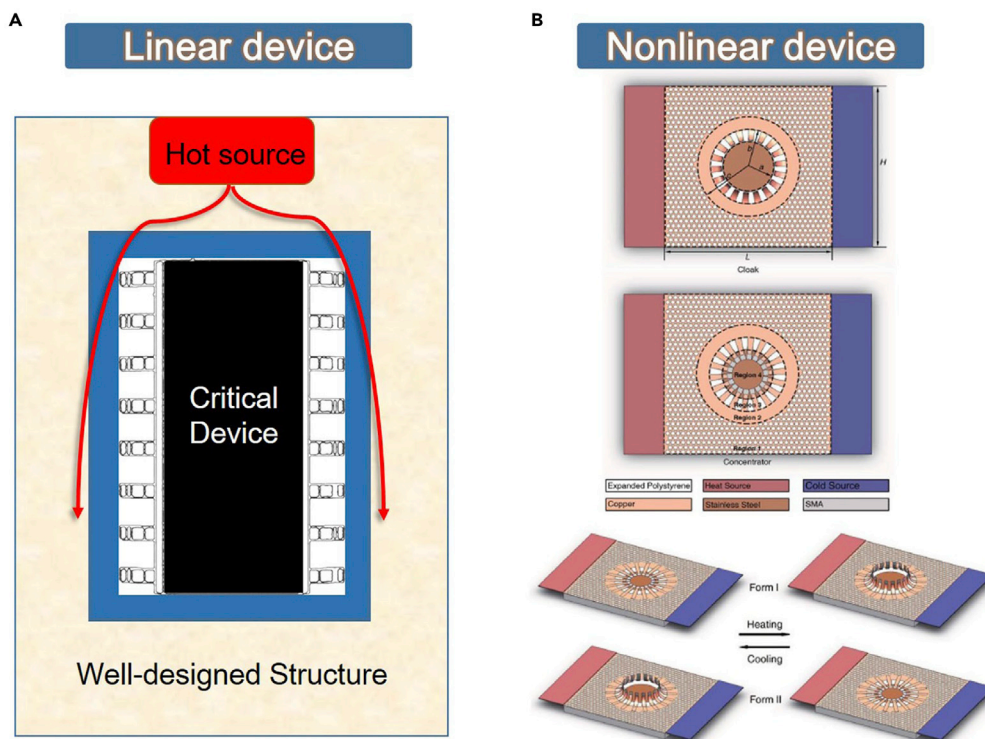


Figure 4. Schematic Diagram and Conceptual Illustration of two Typical Macroscopic Devices

(A) Thermal shielding on PCB. It can protect designated regions from thermal invasion. Well-designed structures are fabricated on the board for guiding heat flow.

(B) Thermal cloak-concentrator device. It can show cloaking or concentrating functionality under different temperature regions, which can be seen as a nonlinear intelligent device.

transformation method and successfully realized encrypted thermal printing (Hu et al., 2019). By tuning the thermal conductivity tensors in different regions of identical unit cells, arbitrary heat signatures can be mimicked. This scheme is promising for extreme heat manipulation. An out-of-plane transformation method was also reported by Li et al. (2018). Besides the transformation theory, Yang et al. designed and fabricated an invisible sensor for simultaneous sensing external thermal and electrical fields with a camouflage feature (Yang et al., 2015). A pre-designed isotropic shell structure was applied for satisfying Laplacian equations of steady thermal and electrical simultaneously. This application not only has practice values but also promotes the fundamental research of Laplacian devices under coupled physical fields. As the thermal conductivities are not temperature related, the above thermal devices can be labeled as linear devices.

The optimization method is also applied for designing linear transformation or Laplacian devices. Different from the analytical approach, the optimization method does numerical optimization by computer and does not need accurate solutions in each position. The result-oriented idea makes it broadly applicable in manipulating heat flow. For instance, traditional cooling methods in electronics always resort to high-thermal-conductivity materials or heat pipes, in which heat dissipated uniformly. Dede et al. first applied the optimization-based method on guiding chip heat flow (Dede et al., 2017); see Figure 4A. They arrayed the optimized copper fiber configuration on PCBs for realizing anisotropic thermal conductivities, which were required by the conventional cloak, concentrator, and rotator based on transformation thermotics. They found that the aim regions assembled with critical electronic elements have 10.5°C temperature reduction after these elaborate designs. This is the first attempt for electronic heat dissipation with thermal metamaterials (Kim et al., 2021). Replacing complex analytical calculations in designing thermal illusion, Sha et al. established an effective topology optimization model for treating this problem (Sha et al., 2020). This method can achieve complicated metamaterial design, which is hard to solve by analytical schemes.

Nonlinear transformation thermotics has led to the concept of intelligent metamaterials. Other than linear devices, the effects of such metamaterials are not static but varying with the ambient. So, it is crucial to find the materials that can change its properties when external environments are changed. A switchable thermal cloak was then experimentally demonstrated (Li et al., 2015) with phase-changing materials (PCMs). Also, thermal cloak-concentrator devices (Shen et al., 2016a) and energy-free thermostats (Shen et al., 2016b) were designed and fabricated. Figure 4B illustrates the cloak-concentrator's working principle conceptually. Temperature-dependent materials make the device adaptive to environments, which can be regarded as a kind of intelligence. Furthermore, by combining nonlinear transformation theory and multi-physics/function design, some more attractive manipulation can be realized. For example, Wang et al. designed a thermoelectric thermostat cloak with a bilayer structure (Wang et al., 2019). Jiang et al. manufactured a multi-physics bifunction device with shape memory alloys (SMAs) (Jiang et al., 2019). This category of nonlinear devices shows wider applicability compared with linear devices. A generalized concept of nonlinear thermal devices contains not only stimulation-feedback devices (passive) but also active field-induced property-changing ones. By adopting active control, reconfigurability will be achieved.

Recently, multiple macroscale thermal calculation schemes have been proposed. Hu et al. proposed a binary-thermal-encoding idea by two typical meta-devices (cloak and concentrator) representing "0" and "1" (Hu et al., 2018). By arraying cloaks and concentrators in specific ways, feature thermal signals can be captured. This is another practical application of transformation thermotics. Besides, with the help of nonlinear thermotics, Wang et al. designed thermal bistability on a nonlinear asymmetrical two-terminal model (, 2020b). This device shows two stable states beyond one boundary condition, which may facilitate designing thermal memory in macroscale. We can expect that macroscale thermal calculation techniques have potential on turning waste heat into wealth, just as a proverb saying "kill two birds with one stone."

Thermal camouflage or illusion is another kind of significant application, which has a direct application in military. In 2014, Han et al. first proposed this concept with a bilayer design (Han et al., 2014b). Then it was generalized to transient cases (Yang et al., 2016). We have also introduced above that Hu et al. and Zhou et al. reported heat-source camouflage schemes (Hu et al., 2018b; Zhou et al., 2018), which could cancel real heat signatures and show fake signals with the transformation method. These designs are all restricted to in-plane observation views. Say, if one detects the signal out of plane, the camouflage or illusion effects will be easily unmasked. To overcome this shortcoming, Li et al. designed a structured thermal surface for out-of-plane observation (Li et al., 2018). They applied transformation method in z-direction and created a three-dimensional space for concealing objects. Whether being detected in or out of plane, the camouflage effects will remain. Later, Peng et al. also developed three-dimensional separated thermal illusions through the spatial transformation in the z axis (Peng and Hu, 2019). More recently, thermal camouflage has been promoted with photonic design of surface films (Qu et al., 2018; Li et al., 2020a; Song et al., 2020; Wang et al., 2020a, Liu et al., 2020). The radiative wave can be well modulated with surface well-designed structures.

Microscopic Application

Heat energy can be utilized to realize calculation or information processing. With the employment of phase-changing materials such as vanadium dioxides, the theoretical models of phononic calculation such as thermal memories (Xie et al., 2011; Ben-Abdallah and Biehs, 2014), thermal rectifiers (Zhu et al., 2014), and thermal transistors (Kubytskyi et al., 2014) were fabricated in experiments. These researches considered conduction, convection, or radiation modes and can be tailored by external physical fields. On the other hand, macroscale counterparts were also proposed, as discussed above. It seems that phononic or thermal calculation has potential advantages in electronic heat management or even replaces the existing electronic computers. But many subsistent challenges such as working speed and reliability still need to be overcome. And the integration of these self-contained elements for cooperative operation is also lack of study.

The passive radiative cooling can effectively reduce the energy consumption in cooling. The fabrication method, which incorporates a certain proportion of glass particles into a polymer film (Zhai et al., 2017), has caused widespread concern owing to its high cooling power and cost advantage. This technology has been industrialized in the United States and China with products used for energy saving and cooling in buildings, transportation vehicles, and agricultural greenhouses. With the reduction of production cost and promotion of performance, the film-cooling industry may expand and replace some traditional

energy solutions. Another application of passive radiative cooling is harvesting energy from the sun and outer space simultaneously (Chen et al., 2019). This method can improve the efficiency of utilizing solar energy, compared with collecting energy from the sun solely (Li et al., 2020a,). Essentially, the heat source and cold source are the sun and outer space, respectively, whose temperatures can reach several thousands of and sub- kelvin. The huge temperature bias is unprecedented in human's history of using energy. This entirely peculiar idea seems to be promising in raising existing solar conversion efficiency.

OUTLOOK

The existing works on thermal metamaterials have provided powerful tools to manipulate heat transfer, including conduction, convection, and radiation. Many functional devices have been designed, and some of them have already been industrialized. However, realization of more potential applications is still a challenge and breakthroughs are expected in both theories and fabrication techniques. From a macroscopic perspective, the application of thermal metamaterials needs to be adapted to more complicated real-world scenarios. For example, synergistic effects of conduction, convection, and radiation should be taken into consideration, or incorporating action mechanisms containing heat, light, mechanical force, and other physical fields request the coupling of multiple metamaterials on single element. From a microscopic perspective, devices with more functions still rely on the study of microscopic mechanisms of carriers such as phonons, electrons, and photons. In particular, the significant particle nature of heat-transfer phonons at room temperature becomes a major obstacle in transplanting the functional devices in wave systems to diffusion systems. Finally, the combination of macro and micro theories or application is another great challenge. A general framework describing diffusion systems ranging from macroscale to microscale needs to be further studied.

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AUTHOR CONTRIBUTIONS

J.W., G.D., and J.H. conceived the idea and designed the frame. J.H. supervised the project. J.W. and G.D. wrote the first draft of the manuscript. All authors commented, edited, and revised the final manuscript.

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