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Regulating thermal radiation for energy and sustainability

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Thermal radiation is electromagnetic radiation generated by the thermal motion of particles in matter, such as electrons, atoms and molecules. It is a universal phenomenon for matter at a finite temperature above absolute zero Kelvin. Thermal radiation plays an important role in a wide range of energy processes from nanoscale to celestial dimensions, ranging from the solar radiation to Earth's energy budget, and from microwave ovens to personal thermal management. Therefore, effective regulation of thermal radiation can have a remarkable broad range of impacts on energy and sustainability, such as geoengineering, desalination, and energy generation and harvesting [1].

The spectral density of radiation emitted by a black body is described by Planck's law (Fig. 1a), with the total power radiated per unit area in turn described by the Stefan-Boltzmann law as the total radiation power $P = \bar{\varepsilon}\sigma T^4$. Here T is the black body's surface temperature, σ is the Stefan–Boltzmann constant, which equals to $5.67 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$. $\bar{\varepsilon}$ is the average spectral and directional emissivity, a value between 0 and 1, which is equal to the ratio of power radiated to that of a blackbody. Planck's law, originating as it does from a statistical mechanical view of photon energy distributions, highlights that the spectral radiance of a thermal emitter is broadband in nature. For example, the Sun is a prototypical blackbody with a surface temperature of ~ 6000 K, thus radiating most of its intensity in the wavelength range of 0.3–2.5 µm, from the ultraviolet to near infrared. Industrial high temperature processes and concentrated solar thermal conversion typically exist in the temperature range of 500–3000 K, and the corresponding spectrum of interest is 1–10 µm. Around ambient temperature (e.g., 250–500 K), the spectrum of interest is 5–50 µm. Therefore, regulating thermal radiation requires accurate control of a broadband optical spectrum. This is a unique difference from other topics in photonics which focus on narrowband or monochromic control.

The key properties to regulate in thermal radiation include emittance (ε), absorptance (α), reflectance (R) and transmittance (T). They are all functions of temperature (T), angle (θ) and wavelength (λ). At a given set of T, θ and λ, they satisfy $\alpha + R + T = 1$ due to energy conservation (Fig. 1b) and $\varepsilon = \alpha$ as a result of detailed balance in reciprocal systems [2,3]. By regulating and optimizing these parameters, the efficiency of various energy processes can be significantly enhanced, including but not limited to energy harvesting, generation and conversion.

Fig. 1c shows the ideal spectra of several important applications of regulating thermal radiation. An ideal solar selective absorber should maximize absorptance of solar radiation at λ = 0.3–2.5 µm, but minimize ε at the working temperature (e.g., λ ~ 2–20 µm at ~ 100–200 °C). A high-performance thermophotovoltaic device should only have a high ε at a narrowband just above the absorption edge of solar cells used, which maximizes the conversion efficiency. On the other side, an ideal sub-ambient radiative cooler should minimize its absorptance of solar radiation, but maximize emittance in the infrared transparent window of the atmosphere (λ ~ 8–13 µm). Besides designing materials and devices with optimal static radiative properties, dynamic tunability is another important dimension to regulate thermal radiation. For instance, an energy-efficient smart window should be able to switch in both solar radiation waveband and thermal emission near room temperature, and independently in the ideal situation [4]. Such switching can be either passive (e.g., temperature, light-controlled) or active.

The past several decades has witnessed remarkable and exciting progress in regulating thermal radiation for energy and sustainability, which stems from advances in fundamental photonic designs, material developments and device innovation (Fig. 1d). For example, the progress in photonics opens a new window to design materials with inaccessible optical properties in a single material [7,10], such as a large direction-dependent emissivity, which can be used to design thermal emitters with efficient heat transfer. The advances in novel materials enable precise and multi-scale controls of radiative properties. For instance, new materials such as W-doped VO_2, flexible electrochromic material, and polyaniline present temperature-dependent and redox-switchable emittance, which are promising for passive and active switching of thermal properties [5,8,11]. Recent developments of nanomanufacturing, roll-to roll manufacturing lead to the creation of exotic structures with accurate control of radiative properties, such as photonic crystals with well-defined wavelength-dependent thermal emissivity, and scalable random photonic radiative cooling materials at low cost [6,9].

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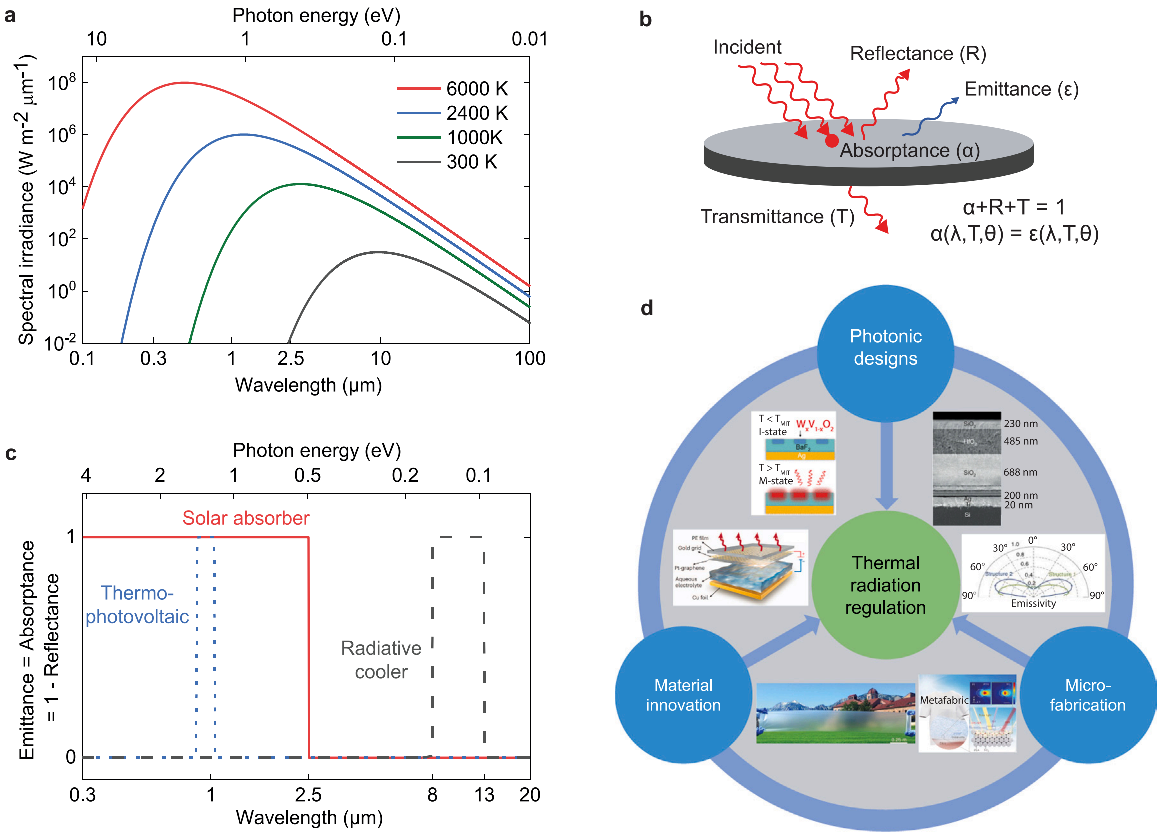

Fig. 1. (a) Radiation spectra of black bodies at different temperatures. (b) illustration of absorptance, reflectance, and transmittance. (c) Ideal spectra for three important applications of regulating thermal radiation: solar absorber, radiative cooler, and thermophotovoltaic. (d) Some of recent key progress on innovations in fundamental photonic designs, material innovation and microfabrication [5–10].

The precise regulation of thermal radiation has already greatly impacted our lives, particularly in term of energy efficiency and sustainability. The global installation of selective solar absorber for solar heating and concentrated solar thermal power plants has reached 479 GW and 6 GW in 2019, respectively, which remarkably improves the life quality of hundreds of millions of people [12]. Radiative cooler has emerged in the market in the last five years, with exciting results of significant energy savings for buildings, safety of electrical and telecommunication facilities under extreme weather, and even for personal comfort. The efficiency of thermophotovoltaic reaches a new record of 40 % in 2022, representing a large leap from the previous record of 32 % [13]. All these progresses originate from advances in fundamental understanding and precise manipulation of thermal radiative properties of materials and devices.

While significant progress has been made in the past years, there are still intriguing challenges to solve ahead, such as how to precisely control radiative properties across broadband from UV to mid-IR, and how to optimize switchable behavior in adaptive radiative materials and devices to adapt different environments. Furthermore, emerging concepts in nonreciprocal thermal emission may allow one to overcome the limits imposed by detailed balance and Kirchhoff's law, enabling improved performance in a range of important applications [14]. This special issue focuses on an interdisciplinary approach to tackling these challenges by generating synergy among fundamental sciences, practical applications, and economic analysis. It aims to capture the most exciting progress in regulating thermal radiation for energy and sustainability, including but not limited to solar steam generation/desalination, radiative cooling, thermophotovoltaic, and industrial thermal processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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