Control of radiative processes for energy conversion and harvesting

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Abstract: We review recent advances in the fundamental understanding and technological applications of radiative processes for energy harvesting, conversion, efficiency, and sustainability. State-of-the-art and remaining challenges are discussed, together with the latest developments outlined in the papers comprising this focus issue. The topics range from the fundamentals of the thermal emission manipulation in the far and near field, to applications in radiative cooling, thermophotovoltaics, thermal rectification, and novel approaches to photon detection and conversion.

OCIS codes: (040.5350) Photovoltaic; (290.6815) Thermal emission; (350.5610) Radiation.

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1. Introduction

The role of radiative processes in the photon energy harvesting and conversion can hardly be overestimated [1,2]. For example, the radiative losses due to electron-hole recombination required by thermodynamics inevitably limit the efficiency of the photovoltaic (PV) energy conversion [3,4]. Still, eliminating non-radiative losses yields open circuit voltage of PV cells close to the thermodynamic limit [5], which can be further increased by photon recycling schemes [6]. Furthermore, energy losses due to thermal radiation severely impact performance of solar-thermal energy converters, and need to be reduced by designing spectrally selective materials, coatings, and external reflectors [7–12]. The success of the thermophotovoltaic (TPV) technology in delivering high heat-to-current conversion efficiency also hinges on the development of highly selective – ideally near-monochromatic thermal emitters [8,13–18]. Highly-spectrally and angularly-selective thermal emitters can even provide a basis for creating photon energy upconversion platforms, which would in turn benefit many photon energy conversion schemes such as PV and TPV [19]. At the same time,

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recent results suggest that enhanced thermal emission can contribute to the night- and daytime cooling of buildings [20–23] and individuals [24] as well as to the reduction of the operating temperature of PV cells [25], which would translate into increased PV efficiency and energy savings. Significant energy savings in solid state lighting technologies can also be achieved by tailoring either fluorescent or thermal emission from light-emitting diodes and new-generation incandescent light sources [26,27].

The radiation processes can be dramatically amplified and tailored in the case of the near-field coupling between the emitter and the absorber of photons, i.e., when the coupling distances are comparable or smaller the dominant wavelength of the radiation [28–37]. This situation is often referred to as a 'breakdown' of the Planck's law governing radiation at short distances [38]. However, it is in fact not surprising, given that the law in its classical form is only valid when 'the linear dimension of all parts considered... are large compared with the wavelength of the ray considered.' The ability to strongly modify radiative processes via near-field coupling can contribute to increasing the efficiency of TPV energy conversion schemes [13,15,16,18,39–41] and provide new means for on-chip thermal management [42] and heat-assisted magnetic recording [43].

The focus issue offers a glimpse at some of the latest developments in the control of radiative processes for energy harvesting, conversion, and sustainability, with contributions covering crucial aspects of the field, including tailoring thermal emission, thermophotovoltaics [39,44–46], thermal emission monitoring, photovoltaics, radiative cooling, and far infrared sensing, as covered in the following sections.

2. Tailoring thermal emission by manipulating the density of photon states

Controlled modification of thermal radiative properties of materials is of fundamental interest and drives many applications, ranging from solar energy harvesting and conversion to nanoscale imaging and sensing, solid-state lighting, and personal comfort technologies. In general, In general, the electromagnetic energy density of radiation in a material is proportional to the available density of photon states (DOS). Accordingly, both light absorption and thermal emission can be tailored (i.e., enhanced or suppressed) via DOS modification.

In particular, excitation of trapped optical modes, such as guiding modes in thin films or volumetric resonances in dielectric nano- and micro-particles results in strong resonant modification of the photon density of states, which in turn modifies both light absorption [47–50] and thermal emission [15,51]. Strong resonant DOS modification is also associated with the excitation of surface phonon or plasmon-polariton modes [32,52]. In many cases, this high photon DOS can only be tapped into through near-field coupling [53,54], however, in combination with the optical confinenent effects, it can result in the strongly modified thermal emission into the far field [23,55,56]. Finally, collective effects [57] in coupled photonic structures with localized excitations, such as nanoparticle clusters, photonic crystals or metamaterials can be used to further shape, enhance and tune thermal emission spectra [7,58–62].

In this focus issue, several contributions present designs and realizations of thermal emitters that utilize photon DOS modification to achieve spectral selectivity. Ghanekar and colleagues calculate spectrally-selective emission from thin films embedded with nanoparticles, and show that the emission spectra can be tunable by varying size, material and volume fraction of nanoparticles [63]. In turn, Dyachenko *et al.* utilize optical confinement and coupling effects to demonstrate spectrally-selective absorber/emitter based on a monolayer of microspheres, which holds promise for high-temperature applications [64]. Roberts *et al.* experimentally demonstrate spectrally-selective thermal emission driven by resonant phenomena in continuous-film Fabry-Perot resonators composed of metal and dielectric layers, which offers a pathway to the development of low-cost emitters amenable to wafer-scale fabrication using standard techniques [65]. Didari and Menguc numerically demonstrate the effect of nanoscale pores on the spectral properties of the near-field heat transfer, which cannot be captured by the effective medium approximation calculations [66].

#250292 Received 16 Sep 2015; published 8 Oct 2015

Buencuerpo *et al.* present an optimization of the photonic crystal structures to leverage light trapping effects for photon-enhanced thermionic emission [67]. Jia and colleagues theoretically demonstrate a possibility to realize coherent far-field thermal emission via excitation of magnetic polariton modes in metal-dielectric-metal nanoshells and nanoshell clusters [68]. Finally, Joulain *et al.* numerically demonstrate a possibility of radiative thermal rectification between planar materials supporting surface phonon polariton modes, which offers useful applications in nanoscale thermal regulation [69]. Liu *et al.* have studied how anomalous optical Anderson localization appear in one dimensional quasicrystal that greatly affect transport properties in the material [70]. This could represent a system where the density of states has been greatly modified, which could ultimately lead to a device that would have its thermal emission controlled.

3. Thermophotovoltaics

One potential area where selective thermal emitters may find significant application is thermophotovoltaics (TPV). Here, the basic concept is to convert thermal radiation into electricity [71,72]. In principle, the efficiency of this process can be quite high, especially at high temperatures, potentially up to 85% [13,73–75]. Possible heat input sources include concentrated sunlight [76], radioisotope decay [77], and waste heat [78]. However, several potential loss mechanisms can sharply limit the realized efficiencies, including most prominently below-bandgap thermal emission [13], radiation lost between the emitter and absorber [79], inefficiencies in heat collection [9], and photovoltaic diode losses [80]. To address these concerns, several foundational studies have established the value of introducing low-bandgap photovoltaic cells, selective thermal emitters, and cold-side short-pass filters.

In this issue, we explore several innovations impacting critical TPV components, along with a system-level demonstration of improved performance. First, we consider the design of emitter structures using resonant structures for thermophotovoltaic applications, which has potential to increase thermal emission to the theoretical maximum at targeted frequencies, even for otherwise weakly-absorbing materials [81]. In parallel, Jurczak *et al*. show that GaInAs cells represent a high-performance, bandgap and thus temperature-adaptive platform for harvesting thermal radiation [45]. Finally, Ungaro *et al*. present experimental work demonstrating the advantage of using carefully designed nanostructures in enhancing solar thermophotovoltaic system efficiencies up to 6.2% [46].

4. Monitoring thermal emission

Along with designing thermal radiation sources and fabricating them for experiments, characterization of their performance can be a highly nontrivial endeavor. It is common that measuring temperatures accurately can be quite challenging at high temperatures. Approaches developed previously include measure thermal radiation spectra via Fourier Transform Infrared spectrometers [82], and IR thermometers [83]. Nonetheless, this can be particularly challenging for materials with wavelength-dependent emissivity [83]. Complementary approaches that could help address these challenges and verify previous results include sensitive measurement of total thermal flux, as well as hyperspectral imaging.

In this issue, two novel characterization techniques are discussed in detail. First, Strojnik and Paez develop a unique approach to rapidly characterizing thermal emission (at 1000 frames per second) [84]. Second, Rowe *et al*. develop an approach to calibrating solar simulators (e.g., for solar thermophotovoltaics) using a cylindrical calorimeter [85].

5. Novel photovoltaic materials and concepts

Photovoltaic cells convert sunlight into electricity, and are subject to the well-known Shockley-Queisser limit for a single semiconductor p-n junction, which is around 31% [3]. Recent experimental work leading to experimental efficiencies of 28.8% in single-junction gallium arsenide have pointed to the need for new strategies to further push the limits of photovoltaic conversion [86]. While a number of candidate technologies have been discussed for improving traditional single-junction cells, a few well-known mechanisms include spectral splitting [87], multijunctions [88], and hot-carrier cells [89].

In this issue, we consider several unique twists on photovoltaic energy harvesting that extend these fundamental approaches. First, Kong *et al*. consider an interesting concept for hot carrier solar cells for enhanced efficiencies [90]. Here, a plasmonic metamaterial absorbs visible light while creating an infrared resonance to protect hot electron states from rapid decay. This could lead to an elevated photovoltage and improved efficiencies. Second, photon tunneling is considered as a mechanism to enhance coupling into a single-mode silicon waveguide [91]. This could lead to novel silicon photovoltaic architectures. Third, a microfluidic beam-steering array is proposed as a potentially dynamic and low-cost method to achieve spectral splitting for substantially higher total conversion efficiencies [92].

6. Radiative cooling

Energy conversion systems such as photovoltaics are also susceptible to unwanted heating that degrades performance, yet avoiding this phenomenon effectively can be challenging. Cooling below an ambient temperature typically requires energy input in the form of refrigeration, which is an energy-hungry process. Passive radiative cooling allows for cooling below the ambient without the input of external energy. Such self-cooling is possible because a radiative thermal body that is exposed to the sky could directly exchange electromagnetic heat energy with the outer space, an enormous and extremely cold heat sink at a temperature of 3 K. Passive radiative cooling could make refrigeration and climate control run more efficiently, saving significant amounts of energy (Fig. 1).

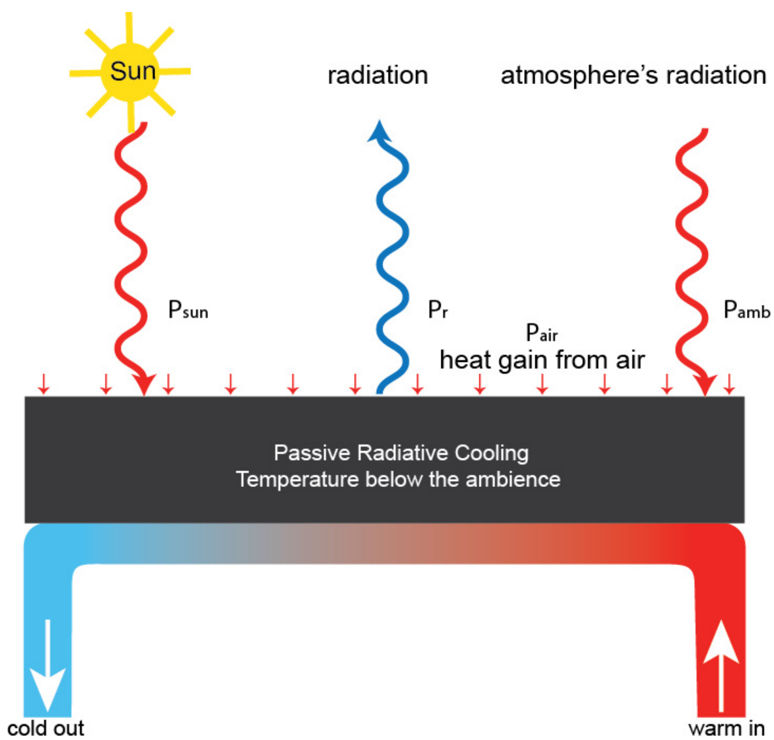

Fig. 1. Energy balance of a passive radiative cooling device. A special thermo-photonic material system needs to be able to radiate efficiently in the mid-infrared (blue arrow), and to repel sunlight and atmosphere's radiation (wavy red arrows), as well as to resist the convection and conduction heat gain from air (straight red arrows).

Nighttime radiative cooling has been extensively studied for decades [23,93–98]. The design for nighttime cooling is straightforward. A blackbody works very efficiently. On the

#250292 Received 16 Sep 2015; published 8 Oct 2015

other hand, to achieve daytime cooling one needs to design special photonic structure that is simultaneously a broadband mirror for solar light and a strong thermal emitter in the atmospheric transparency window. A cover foil that reflects solar radiation has been proposed to realize daytime radiative cooling [20,99]. Recently, an integrated photonic structure was proposed and later experimentally demonstrated to achieve daytime passive cooling [21]. These exciting results show that the cold darkness of the Universe could be used as a fundamental renewable thermodynamic resources for improving energy efficiency on earth.

In this issue, Safi and Munday show that passive radiative cooling can improve the efficiency of photovoltaic cells by lowering the operation temperature below ambient [100]. In particular, they show that by combining specifically designed radiative cooling structures with solar cells, efficiencies higher than the limiting efficiency achievable at 300 K can be obtained for solar cells in both terrestrial and extraterrestrial environments. Their proposed structure yields an efficiency 0.87% higher than a typical PV module at operating temperatures in a terrestrial application. It is also demonstrated that an efficiency advantage of 0.4- 2.6% for solar cells in an extraterrestrial environment in near-earth orbit.

Finally, Wu and Povinelli consider the impact of radiative cooling in the context of gallium arsenide nanowire solar cells [101]. It is found that this cooling effect may be larger in the presence of nanowires than for a planar structure, particular in the presence of certain key materials. The net effect may be to cool cells 10 K below typical expectations.

7. Far infrared sensing

In this section, K. Feng *et al*. review the adjoining *Restrahlen* region of the far infrared spectrum, which extends approximately from 20 to 60 μm [102]. Many materials have a unique far-infrared response in this region that could serve as a molecular fingerprint. However, the authors clearly note that the phonon absorption present in otherwise suitable materials such as III-Vs has greatly limited the development of appropriate sources and detectors to make use of this property. However, compensating for these limitations through emerging techniques and materials could greatly increase prospects for radiative control in the *Restrahlen* region. If successful, such efforts could open up a broad range of new applications, including astrochemical, biological, and industrial sensing [102].

8. Conclusions

In summary, a great deal of new work has been presented in this focus issue on various aspects of the radiative control of thermal emission. It has been shown that radiative control may benefit selective thermal emission, thermophotovoltaics, photovoltaics, cooling, and far infrared optical sensing. These processes can be monitored using emerging techniques in radiative emission monitoring. Given the theoretical predictions of extremely high performance for many of these applications, and the remaining gap in performance in this recently-emerging field, it is likely that a great deal of work will be forthcoming in the near future.

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