A Triple-Mode Mid-infrared Modulator for All-Surface Radiative Thermal Management

Haoming Fang, Wanrong Xie, Xiuqiang Li, Kebin Fan, Yi-Ting Lai, Bowen Sun, Shulin Bai, Willie J. Padilla, Po-Chun Hsu

1 Department of Mechanical Engineering and Materials Science, Duke University, Durham, North Carolina 27708, USA
2 Department of Materials Science and Engineering, HEDPS/CAPF/LTCS, Key Laboratory of Polymer Chemistry and Physics of Ministry of Education, College of Engineering, Peking University, Beijing 100871, China
3 College of Materials Science and Engineering, Beijing University of Chemical Technology, Beijing 100029, China
4 Department of Electrical and Computer Engineering, Duke University, Durham, North Carolina 27708, USA

E-mail: Po-Chun Hsu (pochun.hsu@duke.edu)

Abstract: We demonstrate a mid-infrared modulator that can switch among reflectance, emittance, and transmittance by mechanical actuation. The triple-mode modulation allows heating/cooling for objects with all emissivity, thereby increase the versatility of radiative heat management.

Thermal management is widely used and critical in advanced technology. For instance, batteries, solar cells, vehicles and electronic chips all require careful thermal management to maintain suitable working temperature ranges. On a larger scale, space heating and cooling maintain the indoor temperature all year round but also consume up to 20% of global energy. Among all the thermal management mechanisms, radiation heat transfer is best known for its universality, media-free operation, and large tunability [1]–[6]. For many thermal engineering applications, dynamic control of radiative heat transfer brings superior efficiency and versatility [7]–[10]. However, the design strategy is complicated by the object dependence. That is, when the object is highly emissive (e.g. human body), the ideal cooling device should be transparent to the mid-IR. For low-emissivity objects (e.g. metals), the cooling should be achieved by high-emissivity coating. This dependence on object emissivity limits the applicability of radiative heat managing device, especially for composite objects with a variety of surface finishing.

Here, we demonstrate a triple-mode polymer/metal elastomeric modulator that is able to dynamically switch among emission (E-mode), reflection (R-mode), and transmission (T-mode) to accomplish the management of all-surface passive radiative cooling and heating. As shown in Fig. 1, in E-mode, the IR semi-absorbing elastomer is at zero strain and the largest thickness for absorption. The underlying metal layer has the highest roughness to promote diffuse scattering and further increases the absorption. In R-mode, the film is biaxially stretched, which smoothens the metal reflector and shrinks the elastomer thickness for high reflection. In T-mode, the film is stretched further to reduce the thickness and create voids on the metal film that results in high transmittance.

The emittance (ε) of polymer/metal film is determined by both the polymer thickness and the metal diffuse scattering, as shown in Fig. 2(a). A detailed analysis of these two factors is performed for maximizing the emittance contrast in the modulation range. We define the total effective absorption coefficient (μ) to be the product of the intrinsic absorption coefficient (μp) and the enhancement scattering factor (β). As shown in Fig. 2(b), when the inverse-pyramid texture is introduced to the film, Δε increases to 0.43 at a thickness of 125 μm. In theory, Δε will increase with higher Δβ until reaching the Yablonovitch limit (Fig.3(c)). We calculated the theoretical limit of Δε to be as high as 0.72, suggesting the promising modulation range between E- and R-mode, if the device microstructure is further optimized.

In E-mode (Fig. 3(d)), the modulator has the highest absorptance (emittance) of 78 ± 1% and low transmittance of ~1%. In R-mode (Fig. 3(e)), the reflectance dominates with a value of 60 ± 1%, and the transmittance becomes ~3 ± 1%. In T-mode (Fig. 3(f)), the transmittance of the film rises to 52 ± 2%, while the reflectance and absorptance decrease to 28 ± 2% and 20 ± 1%, due to the isolated metal islands and the reduced SEBS thickness. Fig. 3(g) shows these three mid-IR properties after weighted-averaging over black body radiation when the strain varies from 0% to
This exceptional tunability is stable after 1000 strain cycles with around 10% change, indicating good cycle stability and reversibility (Fig. 3(h)). We also conducted heat transfer measurement to demonstrate the dynamic switching and prove the efficacy of using triple-mode device to achieve heating/cooling for both high- and low-e materials. Finally, as a secondary applications, we demonstrate an 4 x 4 dot pixel IR-camouflage device that can show different thermal radiation by apply the strain pneumatically.

In conclusion, we combine solid mechanics, Beer-Lambert law and light trapping principle to achieve the dynamic switching among emittance, reflectance, and transmittance. The device can achieve smart object-agnostic radiative heat management that have potential applications for electronics, sustainable buildings, IR-camouflage, and personal heat management.

Figure 2 (a) Schematic of the sample model. (b) The emittance difference between E- and R-mode as a function of film thickness. (c) The emittance difference with increasing diffuse scattering as the function of film thickness. (d,e,f) The absorbance, transmittance, and reflectance spectra. The shaded areas represent the resultant heat radiation. (g) Weighted-average properties of the film under biaxial strain (h) 1000 times cycle stability test.

References
[1] A. P. Raman, M. A. Anoma, L. Zhu, E. Rephaeli, and S. Fan, “Passive radiative cooling below ambient air temperature under direct sunlight.” Nature, vol. 515, no. 7528, pp. 540–544, Nov. 2014, doi: 10.1038/nature13883.
[2] S. Fan, “Thermal Photonics and Energy Applications,” Joule, Aug. 2017, doi: 10.1016/j.joule.2017.07.012.
[3] T. Li et al., “A radiative cooling structural material,” Science, vol. 364, no. 6442, pp. 760–763, May 2019, doi: 10.1126/science.aau9101.
[4] Y. Zhai et al., “Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling,” Science, vol. 355, no. 6329, pp. 1062–1066, Mar. 2017, doi: 10.1126/science.aai7899.
[5] L. Zhou et al., “A polydimethylsiloxane-coated metal structure for all-day radiative cooling.” Nature Sustainability, vol. 2, no. 8, Art. no. 8, Aug. 2019, doi: 10.1038/s41893-019-0348-5.
[6] J. Mandal et al., “Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling,” Science, vol. 362, no. 6412, pp. 315–319, Oct. 2018, doi: 10.1126/science.aat9513.
[7] X. Zhang et al., “Dynamic gating of infrared radiation in a textile,” Science, vol. 363, no. 6427, pp. 619–623, Feb. 2019, doi: 10.1126/science.aau1217.
[8] P.-C. Hsu et al., “A dual-mode textile for human body radiative heating and cooling.” Science Advances, vol. 3, no. 11, p. e1700895, Nov. 2017, doi: 10.1126/sciadv.1700895.
[9] C. Xu, G. T. Stiubianu, and A. A. Gorodetsky, “Adaptive infrared-reflecting systems inspired by cephalopods,” Science, vol. 359, no. 6383, pp. 1495–1500, Mar. 2018, doi: 10.1126/science.aar5191.
[10] E. Leung et al., “A dynamic thermoregulatory material inspired by squid skin,” Nature Communications, vol. 10, no. 1, p. 1947, Apr. 2019, doi: 10.1038/s41467-019-09589-w.