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Polymer photonic aegises as near-infrared reflectors

Andrea Lanfranchi[1,*], *Heba* Megahd[1], *Paola* Lova[1], and *Davide* Comoretto[1]

[1]University of Genoa, Department of Chemistry and Industrial Chemistry, 16146 Genoa, Italy

Abstract. Year by year, thermal shielding has seen an increase in importance for reduction of energetic consumption in vehicles and buildings as a passive method of cooling opposed to traditional antiecologic air conditioning. In this work, we report on the design and fabrication of flexible, multilayer polymer photonic crystals films, namely aegises. Exploiting their peculiar optical properties, aegises are designed to act as selective reflectors for the near-infrared radiation, principal cause of radiative heating by sunlight, while keeping a relative transparency in the visible range. Different polymers are used as alternating building blocks, and the efficiency of the fabricated structures is assessed via thermal experiments, achieving efficiencies greater than 25% in heating reduction.

1 Introduction

The rising menace of global warming has attracted widespread attention on the issue of the sustainability of our lifestyle.[1] Among the least environmentally friendly habits, the use of the energy-consuming air conditioning. Indeed, in hot climates it already accounts for a consistent percentage of energy consumption and it is estimated to become a serious issue when taking hold in developing countries such as Brazil of India. In the latter, some models estimate for a minimum of 25 % increase of CO2 emission just for the installation of air-conditioning implants in homes.[2] This is clearly unsustainable in the long run. Therefore, passive methods of cooling such as radiative cooling is on the rise; the idea of combining selective radiative emission in the atmospheric transparency window and reflection of sunlight to achieve a sub-ambient cooling of bodies.[3] Since excessive heating by sunlight is responsible for many problems commonly solved by air conditioning, reflecting sunlight it is a passive method of cooling by itself. Our goal in this regard is to study reflectors for sunlight, specifically structures able to reflect the near-infrared radiation (NIR). Indeed, thanks to molecular vibrations' overtones and combination bands, several materials (including water) absorb light in this spectral region, accounting for almost half of the total energy carried by sunlight.[4]

All-plastics distributed Bragg reflectors (DBRs) can act as reflectors for any selected spectral region. They can in principle be fabricated over large areas via co-extrusion, a technique known in the packaging industry, a scalability making them viable for extensive applications.[5] DBRs are photonic crystals with one-dimensional periodicity, multilayers where the refractive index is modulated periodically in one dimension. The periodicity of these structures is the same order of magnitude of visible (Vis) and NIR wavelengths. Their reflectance spectra show high reflectance values at specific wavelength ranges, corresponding to the photon band gaps. Here, photon propagation is impeded by destructive interference amongst the beams refracted by the interfaces of the multilayer. DBRs show relative transparency between their bandgaps, whose spectral position depends on both the periodicity and the refractive index of the photonic crystal's building blocks. Bandgaps' width and intensity increase with the difference in refractive index of the DBR's building blocks, called dielectric contrast.[6] It is hence possible to design and build structures highly reflecting in the Vis or NIR range, efficiently shielding light absorption.[7]

The result are thin thermal shields made of flexible polymer films, similar to the common food-grade film. We call our structures "aegises" (AEs) referencing the mythological goat pelt worn by the goddess Athena.

2 Results and Discussion

2.1. Design and Materials.

Reflectors were designed via numerical calculations using the well-known transfer matrix method. We considered the reflectance spectra of the aegises themselves, the spectrum of the incident light (in our model, an incandescence lamp) as well as the absorption spectrum and thickness of our test materials, water or paraffine. We used three polymers ranging from common plastics, such as cellulose acetate (CA, n_{600nm} = 1.47)[5] to technical polymers such as Poly(N-vinylcarbazole) (PVK, n_{600nm} = 1.66)[8] or Aquivion (AQ, n_{600nm} = 1.36)[8]. The materials selected allowed to obtain two pairs with increasing dielectric contrast, PVK-CA (Δn_{600nm} = 0.21) and PVK-AQ (Δn_{600nm} = 0.3). Arranging single, double and complex DBRs out of the two pairs we could study the influence of both structure and materials on the aegises efficiency in thermal shielding.

* Corresponding author: andrea.lanfranchi@edu.unige.it

2.2. Fabrication and Characterization.

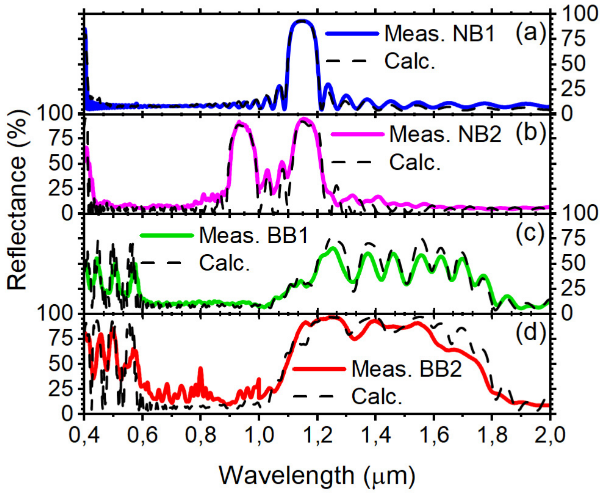

Fig. 1. Reflectance spectra of samples **a)** Narrowband-1 (PVK-CA), **b)** Narrowband 2 (PVK-CA), **c)** Broadband-1 (PVK-CA) and **d)** Broadband-2 (PVK-AQ). Data are solid lines, calculations are dashed lines.

We designed selective NIR reflectors, fully transparent in the Vis range, and fabricated them via spin-coating of PVK and CA. The reflectance spectra of these aegises, NB1 and NB2, shows respectively a single narrow PBG in the NIR range (Figure 1a) and a double narrow PBG (Figure 1b). These results demonstrate the feasibility of fabricating plastic DBR with the desired NIR-reflecting, Vis-transparent properties, in good agreement with calculations (black dashed lines). Furthermore, we fabricated two broadband aegises: BB1, made out of PVK-CA (Fig. 1c) and BB2, made out of PVK-AQ (Fig.1d). despite the two having the same structure, BB2 sample shows the effect of an increased dielectric contrast, with more intense and broader reflection peaks.

2.3. Thermal shielding measurements.

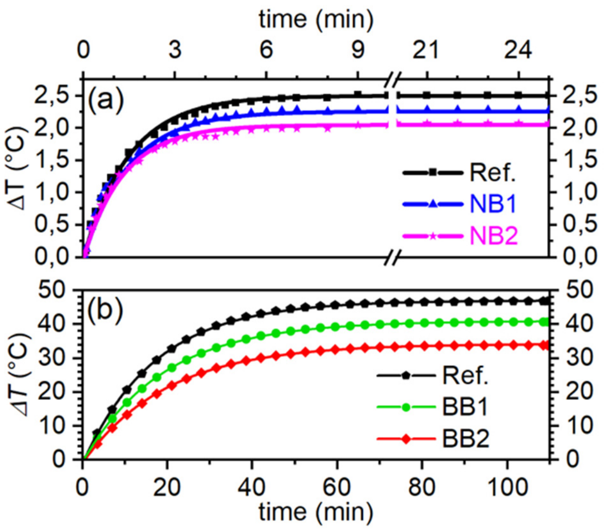

Fig. 2. Thermal curves relative to aegises NB1 and NB2 **(a)** and BB1 and BB2 **(b)**. Data are marks, continuous lines are fittings.

To assess the efficiency of the different aegises, thermal experiments were then performed, measuring the temperature variation of irradiated samples when each aegis or reference was used as thermal shield. The aegises NB1-NB2 were used to shield paraffine (Figure 2a) whereas the BB1-BB2 were used to shield water (Figure 2b). The radiative heating came from a powerful incandescent lamp. Figure 2a shows the effect of improving the structure; NB2, despite using the same material as NB1, being it a more suitable structure has a greater efficiency (18 % heating reduction with respect to the reference, against 10 %). On the other hand, the broadband aegis BB1 was outmatched by BB2 thanks to the superior materials providing better dielectric contrast and improved reflection intensity (13 to 27 %).

3 Conclusions

Our tests showed the functionality in thermal shielding applications of polymer DBRs. We designed and fabricated aegises able to effectively reduce the heating of shielded samples, out of commodity polymers as well as technical ones. The results were close to the theoretical prediction, demonstrating the reliability of our design rationale as well as the fabrication process. Considered the possibility of fabricating aegises on a large scale through industrial processes such as coextrusion, we deem these results interesting in improving the rationale to design all-polymer photonic anti-heating structures, to enhance energy efficiency in the thermal management field.

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