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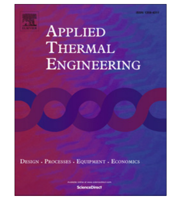

Research Paper

Enhanced thermal transport in polymers with an infrared-selective thermal emitter for electronics cooling

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HIGHLIGHTS

- A new way to improve heat transfer in polymers by thermal radiation is proposed.
- A selective thermal emitter is produced, made of a metallic diffraction grating.
- Controlling the thermal radiation boosted its propagation deep into polymers.
- Effectively propagating thermal radiation in polymers improved their heat spreading.

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ABSTRACT

Passive thermal management has attracted much attention for use in electronic devices. In this study, we propose a novel thermal management technique based on spectral matching between thermal radiation and the infrared optical window of polymers, which are widely used in device encapsulation and packaging. The unique effects of this technique on heat transfer were numerically and experimentally studied. Our numerical analysis confirms that selectively enhancing thermal radiation in the optical window of polymers improved thermal propagation deep into the polymers, reducing local temperature distributions at their surface. In addition, our experiments demonstrate that boosting thermal radiation propagation deep into polymers effectively enhanced their heat spreading and dissipation. Our new method for thermal management in polymers can improve passive thermal management in electronic devices that include polymers.

1. Introduction

Thermal management is essential in electronic devices because of trends such as increasing the integration density of semiconductor chips, reducing cost, saving energy, and miniaturization [1]. In particular, the thermal design of electronic devices is limited by local temperature distributions, generally known as hotspots, decreasing device reliability and performance [2,3]. Although passive thermal management solutions using thermal conduction and convection are preferred in battery-powered electronic devices, these solutions sometimes require large cooling components, making them unusable in many devices. In this work, we study and develop a method of passive thermal management, not requiring a heating medium or external power for heat transport, which effectively uses thermal radiation.

Thermal radiation is the energy emitted from a hot surface as electromagnetic waves. In electronic devices, thermal radiation complements thermal conduction and convection, in turn increasing heat transfer, but radiation contributes relatively little to heat transfer at the operating temperatures of electronic devices, as shown by Planck's law. With recent progress in quantum optics and nanotechnology, spectral control of thermal radiation has drawn interest [4–14], and this technique shows promise for various applications in thermophotovoltaics [15,16], thermal imaging [17], infrared sensing [18], and radiative cooling [19,20]. In particular, research on radiative cooling with spectral control of thermal radiation, which matches the spectrum of thermal radiation and the optical window of the atmosphere (8–13 μm), shows that high-efficiency passive cooling systems using thermal radiation are feasible even at low temperatures [19,20].

Similar to radiative cooling systems, we have also proposed a thermal management technique for electronic devices that use spectral control of thermal radiation [21,22]. This technique works by employing the infrared optical window of polymers, often used

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Nomenclature

a_λ	absorption coefficients (/m)
c_e	correction factor
CTV	coefficient of temperature variation
E	blackbody radiation (W/m^2)
I	light energy (W/m^2)
I_0	incident light energy (W/m^2)
l_λ	penetration depth of thermal radiation (m)
T	temperature (K)

Greek symbols

δ	redefined penetration depth of thermal radiation (m)
δ_m	mean penetration depth of thermal radiation (m)
ε	emittance
λ	wavelength (m)
υ	frequency (1/s)
σ_t	standard deviation of temperature (K)

Subscripts

b	blackbody
e	emitter
m	mean

to encapsulate and package electronic devices. Typical polymers such as epoxy resin, acrylic resin, and polyethylene show lower absorption coefficients in the infrared wavelength region of 3.5–5.5 µm. In this technique, as shown in Fig. 1, heat generated from a heat source encapsulated or packaged in polymers released from the emitter, a device for spectral control of thermal radiation, as thermal radiation matched the optical window of the polymer. The spectrally selective thermal radiation propagates through the polymer into the ambient environment with low absorption loss both because of the enhanced thermal radiation in the polymer's optical window and because of the suppressed propagation at wavelengths with high absorption thanks to the spectral control. This technique is a passive, compact thermal management solution similar to heat pipes [23,24] and graphite sheets [25], though unlike these solutions it actively uses thermal radiation.

This technique is also unique because it can improve heat transfer in polymers, which have low thermal conductivity because of their reduced phonon mean free path (MFP), caused by their random molecular chains [26–28]. Indeed, radiative heat transfer plays an important role in heat transfer and redistribution in polymers. Thermal radiation in the semitransparent medium propagates deep into the medium, preventing increases in surface temperature, which makes it an effective heat transport mechanism compared with thermal conduction [29,30]. In fire science, investigations into radiative heat transfer in polymers have been conducted in hopes of understanding their ignition mechanism [29,31,32]. These studies' findings suggest that spectral control of thermal radiation by using photonics and plasmonics enhances radiative heat transfer in polymers by modulating the spectral features of the thermal radiation radiated to the polymers.

In this study, we propose a new thermal management technique for devices encapsulated in or packaged with polymers, enhancing the heat transport in the polymers by spectral control of thermal radiation. We studied how this technique enhanced heat transport and spreading in polymers both numerically and experimentally.

2. Numerical characterization of the proposed thermal management technique

To evaluate how our technique affects the penetration of thermal radiation into polymers and their heat transport behavior, we propose the characteristic parameter of the mean penetration depth (MPD) of the thermal radiation. This MPD was calculated by using optical measurements to estimate the polymers' absorption coefficients. Based on this MPD, we designed and optimized a spectrally selective emitter (SSE), used for spectral control of thermal radiation. The heat transport properties of the polymers were characterized by comparing their MPDs when using an SSE and spectrally nonselective emitters.

2.1. Description of the mean penetration depth

The exponentially decaying intensity of thermal radiation propagating in an absorbing medium is described by Beer's law. If the medium is assumed to be spatially homogeneous, and the absorption

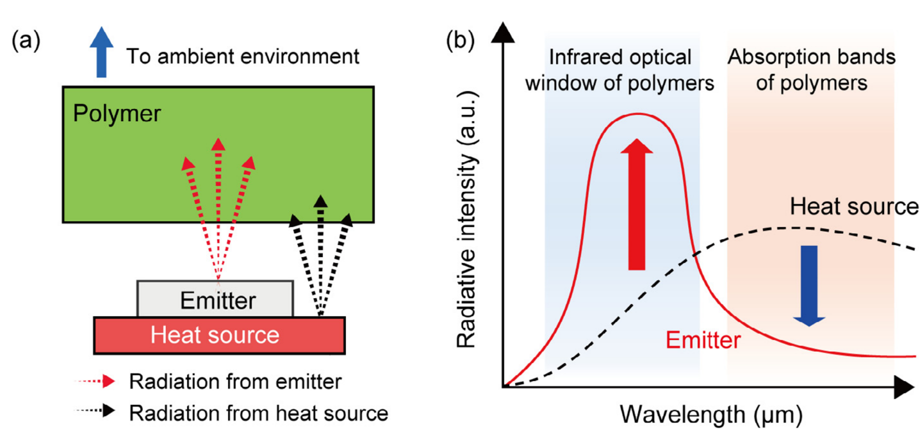

Fig. 1. (a) Schematic showing how spectral control of thermal radiation enhances heat transport in a polymer. (b) Thermal radiation spectrum from the spectrally selective emitter and heat sources as a spectrally non-selective emitter. The thermal radiation from the spectrally selective emitter is concentrated in the infrared optical window of the polymer but it is suppressed in the polymer's absorption bands.