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Li, Sichao ; Simpson, Robert; Submi, Shin

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Enhanced far-field coherent thermal emission using mid-infrared bilayer metasurfaces

Sichao Li, Robert E Simpson, and Sunmi Shin

A classical thermal source, such as an incandescent filament, radiates according to Planck’s law. The feasibility of super-Planckian radiation has been investigated with sub-wavelength-sized sources in the last decade. In such sources, a crystal-dependent coupling of photons and optical phonons is possible at thermal energies corresponding to that of room temperature. This interaction can be used to tailor the far-field thermal emission in a coherent manner, however, understanding heat transfer during these processes is still nascent. Here, we used a novel measurement platform to quantify thermal signals in a GeSbTe/SiO₂ nanoribbon structure. We were able to separate and quantify the radiated, and conducted heat transfer mechanisms. The thermal emission from the GeSbTe/SiO₂ nanoribbons was enhanced by 3.5× compared to that of a bare SiO₂ nanoribbon. Our model revealed that this enhancement was directly due polaritonic heat transfer, which was possible due to the large and lossless dielectric permittivity of GeSbTe at mid-IR frequencies. This study directly probes the far-field emission with a thermal gradient stimulated by Joule heating in temperature ranges from 100 to 400 K, which bridges the gap between mid-IR optics and thermal engineering.

Introduction

Thermal emission is determined by Planck’s law and is generally considered fixed by the material properties. However, many recent studies have tuned the thermal radiation spectrum using photonic crystals, cavities, and gratings. The technique essentially relies on nanostructuring the material’s surface to modify its optical absorption. Kirchhoff’s law states that the equilibrium thermal emission spectrum corresponds to the absorbance of the material, hence the radiated spectrum can be modified. The spectral and temporal coherency in the emission spectrum has been studied by adopting metasurfaces and gratings. The technique essentially relies on nanostructuring the material’s surface to modify its optical absorption. The spectral and temporal coherency in the emission spectrum has been studied by adopting metasurfaces and gratings. The technique essentially relies on nanostructuring the material’s surface to modify its optical absorption. The spectral and temporal coherency in the emission spectrum has been studied by adopting metasurfaces and gratings. The technique essentially relies on nanostructuring the material’s surface to modify its optical absorption.
at frequencies ($\omega_{TO}$) similar to longitudinal optical phonons ($\omega_{LO}$). These confined phonon-photon coupled surface waves have enhanced near-field thermal radiation, which can even exceed the blackbody limits\textsuperscript{25-27}. Our previous study reported 8.5× higher emissivity of the SiO\textsubscript{2} nanoribbons compared to a thin film with an otherwise similar structure. The enhancement stemmed from a strong resonance at thermal wavelengths\textsuperscript{18}. Furthermore, controlling dispersion, via Au-dots/SiO\textsubscript{2} metasurfaces, enabled the enhanced thermal emission by broadening the effective energy range to support SPhPs\textsuperscript{28}.

Herein, we study the influence of a thin polar dielectric layer on far-field emission. Recent studies using different optical experiments on nanophotonic bilayer systems have shown enhanced radiated intensities in the mid-infrared\textsuperscript{8,28-33}. However, it is noteworthy that direct thermal observations have been seldom investigated due to the lack of experimental platforms to study low-energy and low-intensity far-field radiation. We customized nanostructures to emit radiation that can be distinguished from the convection and conduction heat transfer mechanisms. The specimens were integrated into a sensitive thermometer to probe the emissivity. Our novel measurement platform allowed us to quantify thermal signals and to exploit mid-infrared photonic metasurfaces to modulate heat transfer. We compared the emissivity of a bare SiO\textsubscript{2} nanoribbon with the one of Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} (GST)/SiO\textsubscript{2} bilayer nanoribbons. The additional thin layer of a dielectric film with large but lossless refractive index induced highly confined

*Figure 1. Schematics of electric field distribution of (a) confined SPhPs mode generated by the amorphous SiO\textsubscript{2} nanoribbon structure and (b) ultra-confined SPhPs enabled by Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} (GST) thin layer covered SiO\textsubscript{2} nanoribbon at both x-y plane view. The schematics are mimicked from the numerical electrical field distribution for (c) bare SiO\textsubscript{2} and (d) Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5}/SiO\textsubscript{2}, respectively. (e) Plots of calculated thermal conduction due to phonon conduction and radiation heat loss as a function of the sample length. Input emissivity value is 0.17 which is corresponding to the emissivity we got from Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5}/SiO\textsubscript{2} sample at room temperature. (f) Schematic of our sample, with continues GST thin layer deposited on suspended SiO\textsubscript{2} nanoribbon. Zoom-in schematic of the joint of sample and beams highlights that, to avoid electrical leakage from Pt to GST material, we did pre-etching of the GST layer for the electrode pattern areas to make sure the disconnection between Pt and GST. (g) SEM images of our suspended Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5}/SiO\textsubscript{2} nanoribbon sample with (h) Zoom-in image of the sample and beam structure. The width of nanoribbon was designed as 5 μm which is the half of the thermal wavelength (10 μm at room temperature) to further enhance the coherent thermal emission by SPhPs. Final sample width is 5.42 μm (with ~0.3 μm error range from each sample).*
evanescent waves at the interface between Ge$_2$Sb$_2$Te$_5$ and the SiO$_2$, and the tailored energy dispersion of the bilayer metasurfaces could enhance the thermal emission.

We designed bilayer nanoribbon structures to enlarge the surface-to-volume ratios and concomitantly make the radiative heat transfer dominant. A state-of-the-art methodology, which uses a sensitive thermometry platform, was adopted to probe the emissivity of a single nanostructure. The technique involved fabricating finite-sized emitters integrated into a suspended micro-thermometer. The bilayer nanostructure consisted of a thin layer of amorphous-phase Ge$_2$Sb$_2$Te$_5$ (a-GST) on top of an SiO$_2$ nanoribbon. The high contrast in the permittivity ($\varepsilon = \varepsilon' + \varepsilon''$) of the two different layers produced an asymmetric electric field distribution across the top and bottom surfaces as well as at the interface between them. Previously, we used the micro-thermometry platform to directly measure the far-field emissivity of individual nano-objects$^{18, 28, 34}$. Here, we demonstrate the enhanced emissivity using the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ bilayer and report the enhanced emissivity of over 3.5 times that of the bare SiO$_2$ emitter.

**Methods**

**Design of suspended nanoribbon samples.**

We designed a nano-specimen to reveal the dominant heat transfer by conduction with thermal resistance compared to the $G$ by radiation. As shown in Fig. 1(e), the contributions by conduction ($G_{\text{cond}} = \kappa A/L$, where $\kappa$, $A$, and $L$ represent the thermal conductivity, the cross-sectional area and the length of an object) and radiation ($G_{\text{rad}} = 4\sigma A T^3$, where $\sigma$, $A$ and $T$ represent the emissivity, the surface area and the temperature of the object and $\sigma$ is the Stefan-Boltzmann constant) can be distinguished by varying the length of the nanostructures. In general, the higher the aspect ratio of the surface to volume of the emitter, the more significant the heat transfer by radiation. Furthermore, incoherent thermal emission from the solid volume was suppressed by limiting one of the structure’s dimension to be smaller than the skin depth in the mid-IR regime$^{19}$. In this study, we employed nanostructured SiO$_2$ with the thickness of 100 nm, the width of 5 $\mu$m and varied its length from 70 to 800 $\mu$m. Unlike most crystalline solids, amorphous SiO$_2$ rarely presents size-dependent thermal conductivity due to the short mean free path of <100 nm$^{35, 36}$. This fact was used to calibrate our measurement system, as well as to observe the distinct change of the apparent thermal conductivity ($k_{\text{app}}$), which is influenced by radiation when the lattice thermal conductivity is maintained. Furthermore, we introduced a Ge$_2$Sb$_2$Te$_5$ layer on top of the SiO$_2$ nanostructure, which was sufficiently thin to make a negligible contribution to the total heat transported by conduction.

Figure 1(e) shows the estimated thermal conductance by conduction and radiation. In the analytical model, a 5 $\mu$m wide and 130 nm thick Nano Ribbon (NR) was considered with the emissivity of 0.17. These values are the designed and measured values from the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ samples, which will introduce later. Heat transfer by radiation dominates for NRs longer than ~800 $\mu$m. This critical length decreases for the higher emissivity and at higher operating temperatures. Thus, for this study we fabricated NRs with different lengths varying up to 800 $\mu$m.

The Ge$_2$Sb$_2$Te$_5$/SiO$_2$ NRs were integrated into our thermometry micro-devices as shown in Fig. 1(f), where the specimen is located across two suspended metal beams. Notably, the sample specimen and beams are fabricated based on a single unit of SiO$_2$, which gives negligible contact thermal resistance from the beam to heat channel. Generally, the NRs were measure by applying AC-modulated heating and detecting the temperature rises at both beams to evaluate the $k_{\text{app}}$. Importantly, the AC-modulated heating method allowed us to systematically control thermal penetration by varying the heating frequency. Further analysis in the frequency domain could differentiate the influence of the conduction and radiation heat transfer mechanisms. We compared the thermal emissions of bare SiO$_2$ and the bilayer Ge$_2$Sb$_2$Te$_5$/SiO$_2$ NRs. Note, our experiments were entirely thermal-based. They rely on directly probing the far-field emission with a thermal gradient stimulated by Joule heating, which can be different from the optical methods using monochromatic incident waves.

**Sample fabrication.**

We first sputtered a 30 nm thick amorphous Ge$_2$Sb$_2$Te$_5$ layer on a 100 nm thick thermal oxide Si wafer (Fig. S1). As shown in the inset of Fig. 1(f), the Ge$_2$Sb$_2$Te$_5$ area along the sample specimen was set slightly smaller than the SiO$_2$ NR. Next, a 4 nm thick Ti layer and a 76 nm Pt layer were deposited by the e-beam evaporation. Note, the resistivity of Ge$_2$Sb$_2$Te$_5$ abruptly switches from $10^6$ to $10^4$ ohm/m at its amorphous to Face Centered Cubic (FCC) phase transition temperature$^{37}$, therefore the Ge$_2$Sb$_2$Te$_5$ layer was patterned and pre-etched by reactive ion etching (RIE) to avoid direct contact with the Ti/Pt metal layer. Subsequent patterning and etching were used to define the suspended area covering the beams and sample bridge. Lastly, the Si substrate was etched by isotropic XeF$_2$ etching to make the patterned Ge$_2$Sb$_2$Te$_5$/SiO$_2$ bilayer suspended.

**AC-modulated thermometry.**

We employed an AC-modulated thermometry platform (illustrated in Fig. 3(a)) with the measurement resolution of $<1$ nW/K to accurately detect temperature rises in the nano ribbons$^{34}$. The temperature rise at heating side ($\theta_H$) with AC joule heating at 1$\omega$ angular frequency can be detected by the 3$\omega$ harmonic voltage signal ($V_{3\omega}$), which is the well-known 3$\omega$ method$^{38}$. On the sensing side, the temperature rise ($\theta_S$) is measured by detecting the 2$\omega$ harmonic voltage signal ($V_{2\omega}$) with direct current (DC) applied. To further increase the sensitivity, a Wheatstone bridge circuit was applied at the sensing side. The measurement was conducted in high vacuum ($<10^{-6}$ Torr), thus, the convective heat transfer was negligible in
Our experiment. The theoretical temperature distribution for samples with different lengths can be seen from Fig. S2. When there is no significant heat loss (short samples), the temperature distribution along the sample is dominated by phonon conduction, which led to the observed linear trend, as described by Fourier's law (blue line). Nevertheless, when radiative heat loss starts to dominate in the longer samples, the radiative heat transfer coefficient ($h = 4\sigma\epsilon T^4$) needs to be considered, which results in the lower temperature rise along the sample (red line). The exact temperature of the NR can be determined by the voltage signal:

$$\theta_u = 3 \frac{V_{H,3\delta}}{I_{AC}} \left(\frac{dR}{dT}\right)^{-1}$$  \hspace{1cm} (1)

$$\theta_\delta = \sqrt{2} \frac{V_{5,2\omega}(R_S + R_{SP} + R_1 + R_2)}{I_{5,DC}R_2} \left(\frac{dR_2}{dT}\right)^{-1}$$  \hspace{1cm} (2)

where $T$ is the ambient temperature modulated by the temperature controller, $I_{AC}$ and $I_{DC}$ are the AC heating current and DC sensing current, respectively; $R_H$ and $R_S$ are the electrical resistance of the heating and sensing beams, respectively; $R_{SP}$, $R_1$ and $R_2$ are the pair resistance and balance resistance in Wheatstone bridge. The above equations convert an electrical signal into a temperature rise, and are valid for the entire frequency range used in our experiment. Note, the frequency dependent $\theta_\delta/\theta_H$ can represent the modulation of the thermal penetration ($L_P$, we will introduce later) along the whole thermal circuit. In the saturated regime (low frequency) where $L_P$ fully penetrates along the sample length, the $k_{app}$
can be determined; while in the higher frequency regime, where $\theta_F/\theta_B$ is unsaturated, the emissivity can be determined.

### Dielectric constant of Ge$_2$Sb$_2$Te$_5$ in the mid-IR.

To determine the dielectric constant of Ge$_2$Sb$_2$Te$_5$, the Drude and the modified Tauc-Lorentz models were used, following the previous study by Chew et al.$^{19}$ The imaginary part of the permittivity was fitted using the Eq. (3).

$$
\varepsilon''_{\text{GST}}(E, \omega) = \left\{ \begin{array}{ll}
\frac{\Gamma \omega_p}{\omega (\omega^2 + \Gamma^2)} & \text{for } E > E_g \\
A_\text{T} E_0 C (E - E_g)^2 & \text{for } E < E_g
\end{array} \right. 
$$

(3)

The Kramers–Kronig relation was used to calculate the real part of the dielectric constant as:

$$
\varepsilon'_{\text{GST}}(\omega) = \frac{2}{\pi} \int_0^\infty \frac{\omega' \varepsilon''_{\text{GST}}(\omega')}{\omega'^2 - \omega^2} d\omega',
$$

(4)

where $\Gamma$ is the damping factor, $\omega_p$ is the plasma angular frequency, $E_0$ is peak transition energy, $E_g$ is the band gap energy, and $\omega'$ is the angular frequency of measured $\varepsilon''_{\text{GST}}$ range.$^{40}$ All fitted parameters from reported experimental values are summarized in Table S1.

In general, amorphous Ge$_2$Sb$_2$Te$_5$ possesses an almost zero imaginary part of the permittivity in the mid-IR regime and a constant real part of 13.8 (Fig. 2(b)). The lossless optical property within the Reststrahlen band of SiO$_2$ can be utilized to realize highly confined modes within the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ bilayer system. The obtained permittivity was applied to calculate the energy dispersion relation in the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ bilayer NRs.

### Results and discussion

#### Modelling of ultra-confined SPhPs by the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ bilayer.

We modelled the dispersion relation of the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ bilayer and compared it with that of bare SiO$_2$. Full-wave numerical simulations using the finite-element method in frequency domain (COMSOL Multiphysics) were performed to study the confined surface modes supported by the bilayer structures. A bare SiO$_2$ nanoribbon itself can support SPhPs as shown in Fig. 1(a), but when a thin Ge$_2$Sb$_2$Te$_5$ layer is added on top of the SiO$_2$ layers, it supports further confined SPhPs within the Reststrahlen band.

The thickness of the Ge$_2$Sb$_2$Te$_5$ layer was systematically varied to find the optimal thickness to maximize thermal emission. The dispersion energies for Ge$_2$Sb$_2$Te$_5$ thicknesses from 5 nm to 30 nm on a 100 nm thick and 5 µm wide SiO$_2$ nanoribbon were studied. As shown in Fig. 1(c), adding the thin Ge$_2$Sb$_2$Te$_5$ layer increases the allowed wavevectors compared bare SiO$_2$ NRs. This effect is consistent with that predicted in a study by Li et al.$^4$ Approximately 30× higher wavevectors were achieved by adding the 5 nm thick Ge$_2$Sb$_2$Te$_5$ layer. Moreover, the peak $q$, wavevector is red-shifted in the bilayer system, which implies the coupling of the dielectric layer and the SiO$_2$. Similarly, we also analyzed the energy dispersion of the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ bilayer after crystallizing the Ge$_2$Sb$_2$Te$_5$ into its FCC phase, see Supplementary Information (Fig. S3). However, the negligible imaginary component of the amorphous Ge$_2$Sb$_2$Te$_5$ dielectric function deems it more suitable for studying the influence of SPhPs.

We optimized the effect of the nanoribbon width on the dispersion energy. Indeed, we employed narrow, ~5 µm, wide nanoribbons to reduce their cross-sectional area and concomitantly minimize the thermal conducted through the solid volume. We modeled the energy dispersion of the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ infinite thin film and compared it with that of the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ nanoribbon. As can be seen in Fig. 2(d) and Fig. 2(f) respectively, the dispersion of the wavevectors and the propagation length are identical for the thin film and nanoribbons. This result means that the surface waves are confined along the interfaces between SiO$_2$ and Ge$_2$Sb$_2$Te$_5$ layers, rather than the side walls or edges.

#### Enhanced far-field emission from GST/ SiO$_2$ nanoribbons.

We first conducted the thermal conductivity measurement at various temperatures ranging from 100 to 400 K. It is noteworthy that the temperature-controlled measurement allows us to differentiate the radiative and conductive heat transfer. At higher temperatures, radiative heat transfer is dominant. Similarly, we also varied the surface area of specimens by adopting a wide range of lengths from 70 to 800 µm. Larger surface areas should increase thermal emission. Empty devices, without NRs, were also measured to compare with the NR samples such that the effect of NR can be determined. The temperature rises were measured for different heating power in the empty device in both heating ($\theta_H$) and sensing ($\theta_S$) beams, as shown in Fig. 3(b). There is a negligible temperature rise at the sensing beam in response to heating the heater. This measurement directly confirms that there is insignificant background far-field thermal emission between the long metal beams in our device. Thus, we can infer that any radiative heat transfer must be due to the surface of nanoribbons.

Figure 3(c) compares the $k_{app}$ of bilayer Ge$_2$Sb$_2$Te$_5$/SiO$_2$ NR with the bare SiO$_2$ NR. The $k_{app}$ is influenced by both radiation and conduction. Short SiO$_2$ NRs with 20 and 70 µm show the almost bulk-like thermal conductivity over the wide range of temperatures due to insignificant radiative heat loss on the surface. It clearly indicates that nano-emitters need to be designed with high surface-to-volume ratios to detect thermal emission. However, the aspect ratio required increases with the thermal conductivity of the solids, and therefore much longer and thinner suspended nanostructure need to be fabricated, which is technically more challenging. In our experiment, we
chose SiO$_2$ as a polar dielectric with a low thermal conductivity of $\sim$1.4 W/m-K (c.f., Si$_3$N$_4$ with 90 W/m-K, SiC with 490 W/m-K and hBN with 420 W/m-K). Also, importantly, the amorphous SiO$_2$ should not exhibit size-dependent thermal conductivity for the dimensions of our samples, which are down to 100 nm owing to the short phonon mean free path$^{35, 36}$. This design allows us to calibrate our measurement system and quantify the contribution of the heat conduction for different samples. The 30 nm thin layer of Ge$_2$Sb$_2$Te$_5$ on top of the SiO$_2$ has a lower intrinsic thermal conductivity (below 0.5 W/m-K)$^{41}$ than the 100 nm thick layer of SiO$_2$ (1.4 W/m-K) at 300 K, which matches with our fitted effective thermal conductivity $\kappa_{eff}$ in Fig. 4(a).

The thermal emission is greater for emitters with a larger surface. As shown in Fig. 3(c), the $\kappa_{app}$ starts deviating from the bulk thermal conductivity of SiO$_2$ for the 400 $\mu$m and 800 $\mu$m long specimens. One can see that the $\kappa_{app}$ dramatically decreases with the increasing nanoribbon length; indicating that radiative heat loss has been enhanced for the larger surface areas. By comparing the $\kappa_{app}$ of bare SiO$_2$ and the Ge$_2$Sb$_2$Te$_5$/SiO$_2$, we quantified the enhanced thermal emission for the bilayer nanoribbons. In Fig. 3(c), the colored area presents the predicted $\kappa_{app}$ determined by the emissivity, which ranges from 0.15 to 0.25 (0.07 to 0.1) for Ge$_2$Sb$_2$Te$_5$/SiO$_2$ (bare SiO$_2$). At low temperatures, the emitting power is relatively small, and becomes insignificant compared to the thermal conductance in the solid volume. Thus, the $\kappa_{app}$ of most samples is similar to the thermal conductivity of bulk SiO$_2$. Larger $\kappa_{app}$ deviations were observed at higher temperatures. Note that for all the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ samples we controlled the ambient temperature below 400 K, which is well below the amorphous—FCC phase transition temperature ($\sim$ 420 K).
Hence, the amorphous phase of Ge$_2$Sb$_2$Te$_5$ was retained throughout the experiment.

To extract the thermal emissivity of the NRs, we analyzed the temperature rise at different heating frequencies. Effectively, this experiment controls the thermal penetration depth ($L_\omega$). In our thermometry platform the suspended emitter is connected to the heating metal beam, and this generates heat flux parallel to the sample length and thus 1D heat transfer can be considered. The frequency-dependent $L_\omega$ can be expressed by equation (5):

$$L_\omega = \frac{\alpha}{2a_1} = \frac{\kappa}{2pC\omega_1}$$

where, $\alpha$, $\kappa$, $\rho$ and $C$ are thermal diffusivity, thermal conductivity, density and specific heat capacity, respectively. Note that $\omega_1$ represents the angular frequency of the electric current input. As indicated in the inset of Fig. 3(d), the higher heating frequency results in a shorter $L_\omega$. Consequentially, using the heating frequency to control $L_\omega$ effectively provides a means to control the surface area influenced by the heating, and correspondingly the emitted thermal power. We analyzed the frequency-dependent temperature rises at the heating and sensing beams using Eq. (6):

$$\frac{\theta_S}{\theta_H} = \frac{1}{\cosh(a_2L_\omega) + \frac{\kappa_1A_1a_1}{\kappa_2A_2a_2} \sinh(a_2L_\omega) \tanh\left(\frac{1}{2}a_1L_1\right)}$$

where 1, 2 represents the beam and NR sample respectively.

$$(a_1)^2 = \frac{j\omega}{a_1^2}$$

$$(a_2)^2 = \frac{j\omega}{a_2^2} + \frac{hP_2}{\kappa_2A_2}$$

Where the $h$ is the radiative heat transfer coefficient ($h = 4\sigma\varepsilon T^3$), $P_2$ is the perimeter of the sample cross-section.

In the low frequency regime, the $L_\omega$ becomes much longer than the length of samples, where the $\kappa_{app}$ was determined. The $\kappa_{app}$ is influenced by both conduction and radiation. By fitting the measured overall frequency-dependent temperature rises with the modelled ones, we separated the influence of the two different heat transfer mechanisms. In Fig. 3(d), the colored area represents the radiative heat loss carried by SPhPs. By applying the $\kappa_{ilt}$ and considering radiative heat loss for an emissivity of 0.23, the modelling data (red solid line) can fully fit with our experimental data (black diamonds), as plotted in Figure 6.
Conclusions

We studied the enhanced far-field thermal emission from mid-IR bilayer nanostructures. We designed bilayer nanoribbon structures that enhance the radiative heat transfer to the point that it dominates over other heat transfer mechanisms. This enhancement enabled us to detect the emissivity of individual nanoribbon structure by making meticulous measurements of the apparent thermal conductivity. The emitter was integrated into a sensitive thermometry platform, and we performed temperature- and frequency-dependent measurements to separate the radiative and conductive heat transfer mechanisms. The separation enables us to evaluate the emissivity and thermal conductivity of specimens simultaneously. This direct measurement of the heat transfer revealed greater than adding a thin high refractive index layer, Ge$_2$Sb$_2$Te$_5$, to the nanoribbon could enhance radiative heat transfer by 3.5×. Our analytical and numerical modeling showed that the electric field is highly confined along the interface of the Ge$_2$Sb$_2$Te$_5$ and SiO$_2$, which leads to the observed enhanced radiative emission to the far-field. The results show strong and direct experimental evidence for the super-Planckian mid-IR thermal emissions at low temperatures. This experimental verification was only possible due to our sensitive platform for separating conductive and radiative heat transfer in nanodevices.

Data Availability

The data that support the findings of this study are available from the corresponding author on reasonable request.

Author Contributions

S.L. and S.S. devised the experimental designs. S.L., R.S. and Y.P. prepared samples. S.L. conducted the thermal measurement and numerical modeling. All authors discussed the results and wrote the manuscript.

Conflicts of interest

There are no conflicts to declare.

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References
