

RESEARCH ARTICLE

Tunable Asymmetric Thermal Transport via Phonon Polaritons Enhancement in Nanophotonic Cavities

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ABSTRACT

Dynamic control of nanoscale heat flow is a pivotal challenge for thermal management in advanced integrated circuits and high-power compact devices. Conventional phonon-based modulation strategies are fundamentally restricted by the intrinsic crystalline lattice, exhibiting limited performance in modulation amplitudes and directional transport. This necessitates the exploration of new physical paradigms. Phonon polaritons, hybrid quasiparticles arising from phonon-photon coupling, bridge thermal and electromagnetic transport, thus opening transformative possibilities for photonics-based thermal control. Here, we demonstrate ultrahigh heat flow enhancement and active directional control of heat conduction through phonon-polariton coupling enabled by nanophotonic cavities. Asymmetric graphene nanoresonators patterned on suspended silicon dioxide nanobeams launch and confine surface plasmon-phonon polaritons (SPPPs) that transport heat along the structure. By tailoring cavity geometry, the effective thermal conductivity increases from 1.48 to 4.73 Wm⁻¹K⁻¹, corresponding to a resonant enhancement of up to 219%. This enhancement arises from Fabry-Pérot resonances and Purcell-type amplification of SPPP modes, while structural asymmetry further induces asymmetric SPPP excitation, yielding a thermal rectification ratio of 143%. Our results uncover an optical mechanism for amplifying and directing heat flow, expanding the application of nanophotonics into the thermal domain and establishing a foundation for polariton-based reconfigurable thermal circuitry and optically controlled nanoscale heat management.

1 | Introduction

The relentless advance of transistor technology towards physical limits, coupled with ever-increasing power densities, has made thermal management from ultrahigh heat flux a critical bottleneck for next-generation electronics. To mitigate heat accumulation and prevent thermal damage, active and efficient control of heat flow at the nanoscale is urgently required. However, current strategies—dependent on modifying intrinsic

lattice properties (e.g., strain engineering [1, 2], doping [3, 4], and moiré superlattices [5–7])—are fundamentally constrained by their reliance on phonon scattering and offer limited potential for breakthroughs in thermal dissipation. This compels the exploration of new physical paradigms that transcend conventional phonon transport.

Phonon polaritons, hybrid quasiparticles arising from the coupling between optical phonons and electromagnetic fields [8–11],

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can be excited via external electromagnetic or thermal stimuli [12]. They exhibit exceptional characteristics such as high propagation speeds, long coherence lengths, and subwavelength confinement [8, 10, 13, 14], making them valuable for applications in sub-diffraction imaging [15, 16], electroluminescence [17], and nonlinear optics [18]. In the realm of thermal transport, phonon polaritons have been demonstrated to enable near-field radiative heat transfer (NFRHT) to surpass the blackbody limit by several orders of magnitude [19–26]. Furthermore, coupled polaritons endow NFRHT between different media with quasi-monochromaticity and dynamic tunability [24–26]. Beyond radiative heat transfer, researchers have further explored their potential in heat conduction. Recent theoretical [27, 28] and experimental [29–33] studies have further shown that phonon polaritons can function as additional heat carriers, significantly influencing thermal transport in polar dielectric films [29, 30, 32, 33] and nanowires [31], thereby bridging the fields of nanophotonics and phononics.

Unlike conventional phonons [34], phonon polaritons exhibit an intimate coupling with the dielectric response of materials and surrounding electromagnetic fields. This fundamental distinction enables active control beyond traditional phonon scattering, using optoelectronic means such as photoinjection [35] and electrostatic gating [36, 37]. Inspired by nanophotonics, resonant nanostructures can dramatically enhance electromagnetic near fields and light-matter interactions [38–41], enabling the efficient propagation and interaction of phonon polaritons within cavities and allowing for precise control over these quasiparticles. Despite this promising outlook, experimental demonstrations of phonon-polariton-mediated thermal modulation remain scarce, and the underlying physical mechanisms are far from fully understood, representing a critical gap in current research.

Here, we demonstrate bias-dependent excitation and active modulation of phonon polaritons by integrating graphene nanoresonators of varying cavity widths onto one end of a 50 nm-thick free-standing silicon dioxide (SiO_2) nanobeam. These nanoresonators launch surface plasmon–phonon polariton (SPPP) modes at the graphene/ SiO_2 interface, as confirmed by the scattering-type scanning near-field optical microscopy (s-SNOM) and electron energy-loss spectroscopy (EELS). Among resonators with widths of 0 nm (pristine graphene), 100, 150 and 220 nm, the 150 nm cavity demonstrates the largest thermal conductivity enhancement—up to 219% relative to the bare SiO_2 beam—demonstrating the resonance-dependent nature of polariton-mediated heat conduction. Furthermore, by launching SPPP modes from the resonator end toward the bare beam, we realize thermal rectification with up to 143% heat flux asymmetry under differential thermal excitation. Boltzmann transport equation (BTE) simulations elucidate that this rectification arises from ballistic polariton propagation combined with the asymmetric resonator configuration. Our findings establish a new paradigm of polaritonic resonance engineering for controlling thermal transport, introduce a novel optical degree of freedom for the design of thermal-functional devices, and open a frontier for the application of nanophotonics in thermal science.

2 | Results and Discussion

2.1 | Device Fabrication and Structural Design

Schematics of the experimental measurement device and fabrication process are illustrated in Figure 1a and Figure S1, respectively. The SiO_2 thin film was fabricated through a thermal oxidation procedure. Two S-shaped Au electrodes were deposited onto a 50-nm-thick SiO_2 layer via electron-beam physical vapor deposition (EB-PVD), serving dual purposes as resistive thermometers and heaters. Electron beam lithography (EBL) was employed to pattern the SiO_2 film into nanoribbons with a width of 6.5 μm and length of 25 μm . The surrounding SiO_2 layer was subsequently removed by reactive ion etching (RIE) to expose the underlying Si substrate. A follow-up dry etching was conducted to fully suspend both SiO_2 nanobeam and S-shaped Au sensors, thereby enhancing the sensitivity of thermal measurements. The device fabrication process was monitored by optical microscopy, and the representative images are provided in SI (Note S1).

To examine the effects of graphene nanoresonators, periodic nanophotonic cavity arrays were defined on graphene sheets via EBL followed by oxygen plasma etching. The patterned graphene was then transferred onto one end of the SiO_2 nanobeam by using micromanipulator probes. Three sets of graphene nanoresonators with widths, W , of 100, 150, and 220 nm were fabricated (Figure 1e–g). Scanning electron microscopy (SEM) characterization confirmed uniform and well-defined cavity structures (Figure 1i–k), with the measured widths closely matching the design specifications. Further quantitative statistical analysis revealed small relative standard deviations ($< 6\%$) for the cavity widths, demonstrating high geometric consistency of the periodic grating structures (see Note S1).

2.2 | Polaritonic-modulated K via Graphene Nanoresonators

Thermal conductivity measurements were conducted employing an H-type sensing apparatus, as described in our previous work [42–44] (see Note S2). The experiments were carried out within a vacuum chamber ($< 1 \times 10^{-3}$ Pa) equipped with a precise temperature control stage. The direction of heat flow could be reversed by alternating the heater and thermometer roles of the two S-shaped sensors, allowing measurements under both forward and reverse configurations. To extract the intrinsic phonon thermal conductivity of SiO_2 and evaluate the effect of thermal radiation, we first measured a bare SiO_2 nanobeam (designated as sample #1). The temperature rise ratio between the sensing and heating sides exhibits a declining trend at elevated temperatures (Figure 2a), which can be attributed to exacerbated radiative dissipation. Following the approach by Li et al. [33], the thermal emissivity of the SiO_2 nanobeam was determined to be 0.36 (see Note S3), a value comparable to their reported results. Upon applying this radiation correction, the extracted actual thermal conductivity of the bare SiO_2 nanobeam (Figure 2b) is in good agreement with the reported bulk value [45].

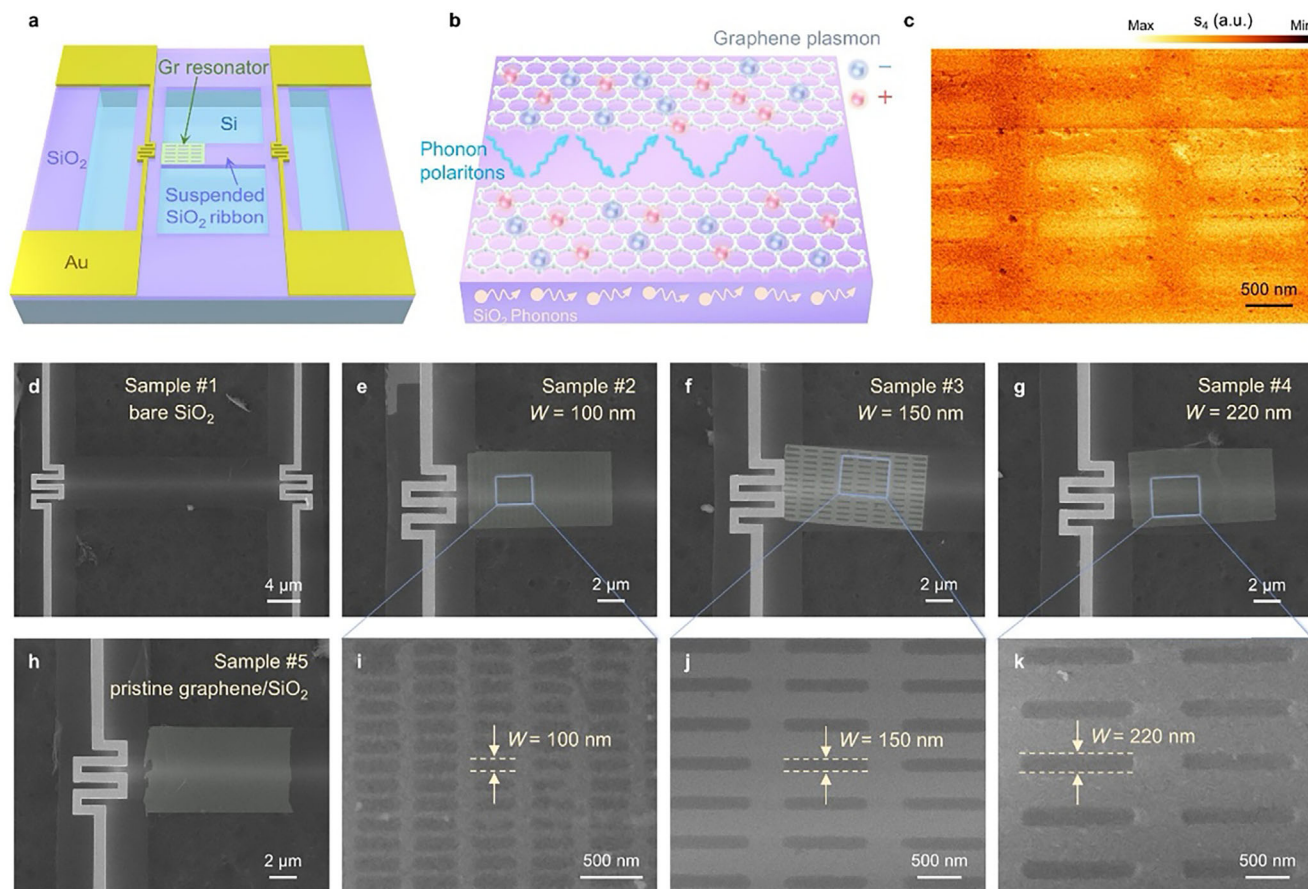


FIGURE 1 | Characterization of SiO₂ nanobeam and thermal measurement devices. (a), Schematic illustration of the measurement device of SiO₂ nanobeam. (b), Schematic illustration of the generation of phonon polaritons through the hybridization of graphene plasmons and SiO₂ optical phonons, and subsequent propagation within the nanoresonator structure. (c), Near-field image of the s-SNOM signal (amplitude s_4) acquired from a 220nm-wide graphene nanoresonator at an excitation frequency of 27.9 THz. (d), SEM image of the bare SiO₂ nanobeam (designated as sample #1), flanked by S-shaped electrodes. SEM images of three SiO₂ nanobeams with graphene nanoresonators placed at one end, displaying cavity widths of 100 nm (e, sample #2), 150 nm (f, sample #3), and 220 nm (g, sample #4), respectively. (h), SEM image of SiO₂ nanobeam with a pristine graphene sheet at one end (designated as sample #5). The contours of all graphene nanoresonators and sheets are highlighted by light green masks. The dimensions of all graphene nanoresonators and sheets are approximately 6.5 $\mu\text{m} \times 10 \mu\text{m}$. Magnified SEM images of the graphene nanoresonators with cavity widths of 100 nm (i), 150 nm (j), and 220 nm (k).

The pristine graphene sheet was subsequently transferred onto one end of the suspended SiO₂ nanobeam to fabricate graphene/SiO₂ heterostructures (sample #5) for thermal characterization. By decoupling the phonon contribution of graphene and the radiative heat leakage to the environment from the total apparent thermal conductivity (see Note S4), we extracted the effective thermal conductivity (κ_{eff} , Figure 2c). The partially graphene-coated SiO₂ nanobeam (sample #5) demonstrates an enhanced thermal conductivity compared to the bare SiO₂ reference (sample #1), with the enhancement growing more pronounced at elevated temperatures and peaking at 2.68 $\text{W m}^{-1} \text{K}^{-1}$ at 393 K. Drawing upon prior investigations on metal-dielectric systems, we attribute this behavior to graphene acting analogously to a metallic coating on polar dielectrics: it emits high-momentum electromagnetic evanescent fields [46, 47] that couple with optical phonons in SiO₂, thereby exciting phonon polaritons [29, 32, 33]. Serving as additional energy carriers, we posit that these polaritons dominate the observed enhancement. Furthermore, the intensified lattice vibrations at higher temperatures increase the

density of these phonon polaritons, giving rise to the nonlinear enhancement of thermal transport with rising temperature.

To further substantiate the observed phonon polariton-mediated thermal transport, graphene nanoresonators with varying cavity geometries were fabricated and transferred onto the SiO₂ nanobeams (samples #2, #3, #4, Figure 1e–g) to tailor electromagnetic polariton launching through Fabry–Pérot (FP) resonances [48, 49]. Scattering-type scanning near-field optical microscopy was employed to characterize the graphene/silicon dioxide (Gr/SiO₂) heterostructure. An amplitude image acquired at an excitation frequency of 27.9 THz (sample #4, Figure 1c) confirmed the presence of an extra electromagnetic resonance mode excited in the heterostructure, which is confined within the FP cavity arrays at a frequency below the lower limit of the Reststrahlen band (32.7 THz) of bare SiO₂.

The total apparent thermal conductivity of the SiO₂ nanobeam partially covered with graphene nanoresonators comprises four

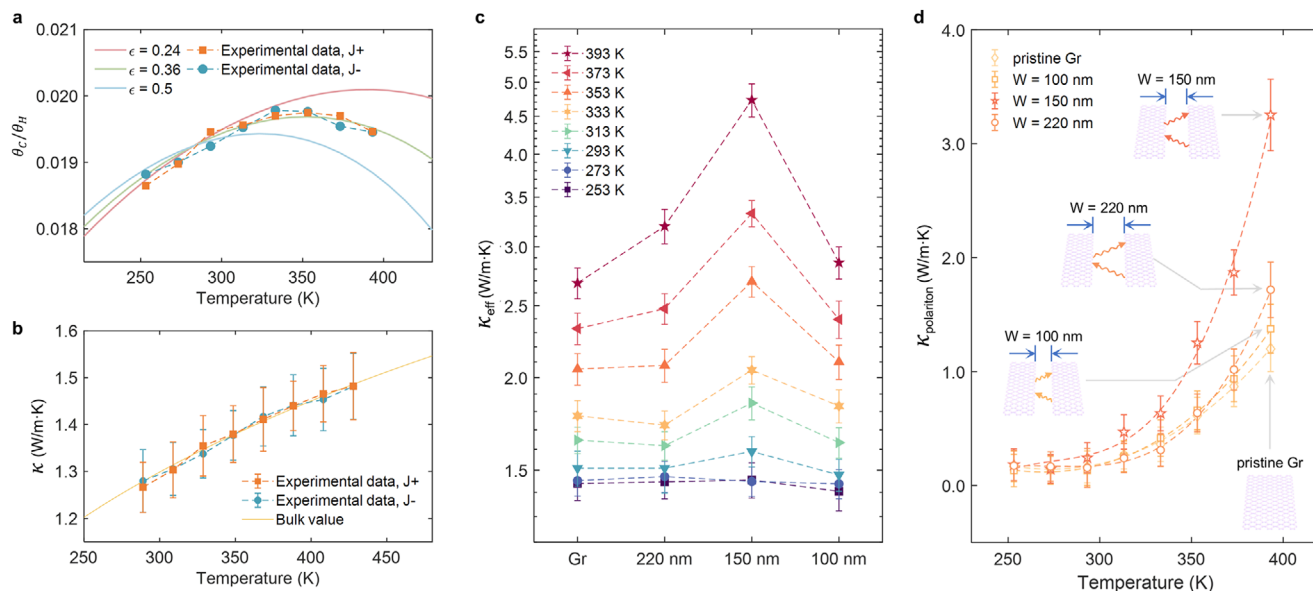


FIGURE 2 | Thermal transport characteristics of SiO₂ nanobeam modulated by graphene nanoresonators. (a), Fit of the temperature rise ratio between the sensing and heating ends to the predicted radiative heat loss, yielding a best-fit emissivity of 0.36. (b), Thermal conductivities of sample #1 in both heat flow directions at different temperatures. (c), Effective thermal conductivities of samples #2 to #5 within the experimental temperature range. (d), Extracted polariton-mediated thermal conductivities of samples #2 to #5.

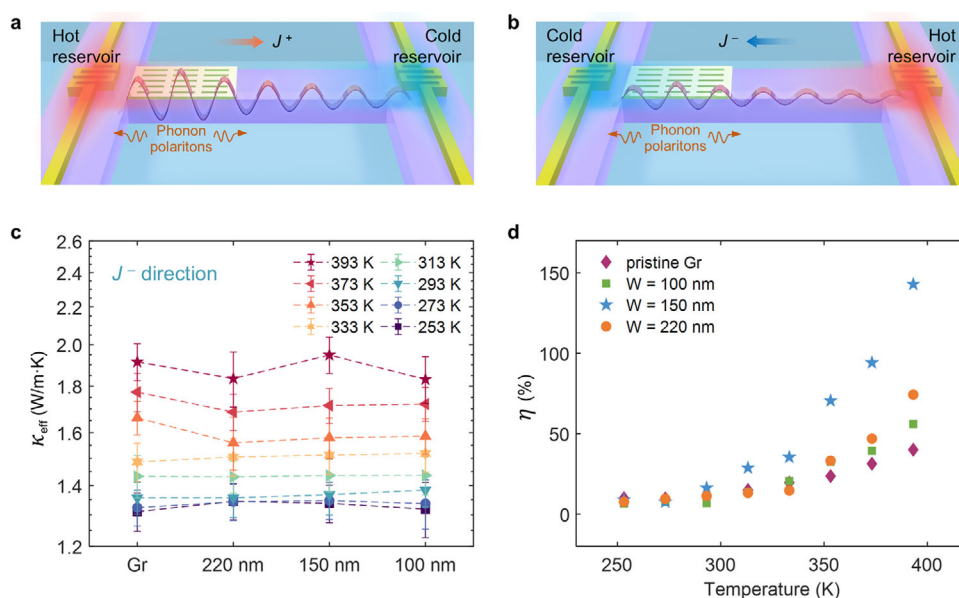


FIGURE 3 | Asymmetric thermal transport of SiO₂ nanobeam. Schematic illustration of phonon polariton propagation under the conditions of two reverse heat flow directions (a, b). The orange arrow denotes the forward heat flow direction J^+ from the left side to the right side, and the blue arrow signifies the reverse heat flow direction J^- from the right side to the left side. (c), Effective thermal conductivities (κ^-) of samples #2 to #5 in the J^- heat flow direction. (d), Thermal rectification coefficients (η) of samples #2 to #5, quantifying the degree of asymmetry in heat transfer.

contributions: intrinsic SiO₂ conductivity, graphene phonon contribution, radiative heat loss to the environment, and phonon-polariton-mediated conductivity. The thermal conductivity values presented herein (κ_{eff} , Figure 2c and 3c) refer to the effective thermal conductivity, obtained by considering effects of the graphene phonon contribution and radiative losses (see Note S4). Compared to the bare SiO₂ reference (sample #1, Figure 2b), the nanoresonator-coated samples exhibit clear thermal conductiv-

ity enhancement, with the magnitude contingent upon cavity geometry (Figure 2c). As the cavity width reduces from 220 to 150 nm, the thermal conductivity increases progressively, reaching 4.73 Wm⁻¹K⁻¹ at 393 K, substantially exceeding the phonon thermal conductivity. However, upon further narrowing the width to 100 nm, the thermal conductivity precipitously drops, approaching that of the pristine-graphene-coated nanobeam (sample #5). The thermal conductivity attributed to phonon

polaritons, $\kappa_{\text{polariton}}$, was quantified as the difference in thermal conductivity between the effective and the pure SiO₂ conductivities (Figure 2d), which demonstrates an increasing trend as temperature increases and $\kappa_{\text{polariton}}$ is the highest for the nanoresonator with a width of 150 nm (3.25 Wm⁻¹K⁻¹). These results not only corroborate the role of thermally excited polaritons in heat transfer, but also underscore their profound sensitivity to resonator geometry during excitation and propagation.

2.3 | Asymmetric Heat Conduction via Resonance Asymmetry

We next investigated how the asymmetric placement of graphene nanoresonators affects heat transfer. The heat flow direction is defined as the J^+ direction when the resonator is located at the hotter end (Figure 3a), and as the J^- direction when located at the cooler end (Figure 3b). The thermal conductivity data in Figure 2c,d is results for the J^+ direction. As depicted in Figure 3c, positioning the nanoresonators at the cooler end (J^- direction) attenuated polariton generation due to the lower excitation temperature, yielding a weaker modulation effect compared to the placement at the hotter side (J^+ direction). Constrained by the low intrinsic thermal conductivity of the samples, our direct current thermal characterization method requires a substantial temperature difference between the heating and sensing ends to ensure measurement accuracy. This large thermal bias also amplifies the asymmetry in polariton excitation between the two heat flow directions, thereby further magnifying the thermal rectification effect. Having ruled out influence from graphene thermal radiation and the temperature dependence of its thermal conductivity, the extracted effective thermal conductivity reveals a pronounced directional asymmetry, realizing a robust thermal rectification (defined as the ratio $\eta = (\kappa^+ - \kappa^-)/\kappa^-$, where κ^+ and κ^- are the effective thermal conductivities corresponding to the J^+ and J^- directions, respectively) (Figure 3d).

The ratio is found to be strongly dependent on both excitation temperature and cavity width. Among all devices, sample #3 represents optimal rectification performance, with η increasing monotonically with temperature and reaching 143% at 393 K. For other samples, no significant rectification is observed below 350 K. Above this threshold, however, sample #4 exhibits a marked increase compared to sample #5, primarily due to its higher thermal conductivity in the J^+ direction. To exclude extrinsic sources of asymmetry, control experiments on the bare SiO₂ nanobeam (sample #1) showed a variation of less than 2% between the two opposite heat flow directions (Figure 2a,b), falling entirely within measurement uncertainty (see Note S6). These results decisively confirm that the observed thermal rectification originates from the asymmetric excitation of phonon polaritons, rather than external geometric or environmental artifacts.

2.4 | Graphene-Induced Surface Plasmon-Phonon Polaritons

To achieve a comprehensive understanding of the observed thermal conductivity enhancement, we developed an analytical model to describe the modulation of phonon polaritons induced by graphene nanoresonators. Note that the propagation and

distribution characteristics of surface phonon polaritons (SPhPs) are primarily governed by the relative dielectric properties of the polar dielectric and its adjacent interfacial material. By replacing air with graphene at the interface, the interfacial polariton modes are expected to undergo significant modulation [30, 50]. For a metal-dielectric interface, the dispersion relation of interfacial polariton modes can be expressed as [51]

$$q_{sp} = \frac{\omega}{c} \sqrt{\frac{\epsilon_r(\omega)\epsilon_m(\omega)}{\epsilon_r(\omega) + \epsilon_m(\omega)}} \quad (1)$$

where ω and q_{sp} denote the polariton frequency and wavevector, respectively, ϵ_r and ϵ_m represent the permittivity of the dielectric and the metal, respectively, and c is the velocity of light (see Note S7). The dielectric function of SiO₂, ϵ_r , is extracted from the experimental data by Palik [52], as shown in the upper panel of Figure 4a. According to the dispersion, the density of states (DOS) of interfacial modes is given by $D(\omega) = \text{Re}(q_{sp})/(2\pi v_g)$ [53], where $v_g = \partial\omega/\partial(\text{Re}(q_{sp}))$ (Figure 4a). Thus, due to its semi-metallic nature and tunable conductivity, graphene exhibits plasmonic behavior akin to that of conventional metals, making it a compelling two-dimensional alternative for launching surface phonon polaritons [46, 54, 55].

Conventionally, SPhPs that exhibit surface-confined wave propagation—characterized by a vanishing wavevector component normal to the surface—can exist only within a specific spectral range known as the Reststrahlen band (R-band), which lies between the transverse optical (TO) and longitudinal optical (LO) phonon frequencies. Within this band, materials like SiO₂ exhibit a negative real part of their permittivity, manifested as the sharp peak in the calculated DOS within the R-band (Figure 4a). Intriguingly, our calculations also reveal a distinct peak in the DOS at lower frequencies, outside the conventional R-band. This indicates the emergence of an additional resonance mode induced by the graphene coating. Owing to their hybrid nature, surface plasmon-phonon polaritons (SPPPs) arise from the coupling between graphene plasmons and substrate phonons. Similar hybrid modes have been observed in the infrared near-field microscopy studies of metal-dielectric heterostructures [39].

To directly verify the existence of the additional SPPP modes, EELS measurements were performed on the Gr/SiO₂ heterostructure. Figure 4b illustrates the experimental setup of EELS based on a scanning transmission electron microscope (STEM, see Note S8). Two samples, i.e., Gr/SiO₂ and bare SiO₂, are prepared using the same fabrication procedure as in the thermal conductivity measurement to ensure consistency. Both samples display a clear polaritonic peak in the energy range of 120–150 meV. Notably, analysis of the full width at half maximum (FWHM) of these peaks reveals that the Gr/SiO₂ heterostructure consistently exhibits broader spectral features compared to bare SiO₂, as shown in Figure 4c. Furthermore, we compared the normalized intensity distributions of the spectra of both samples. As shown in Figure 4d, the high-energy portion of the spectra (above ~135 meV) is nearly identical for both Gr/SiO₂ and bare SiO₂, corresponding to conventional SPhPs. However, the Gr/SiO₂ spectra show a distinct extension toward lower energies, indicating the emergence of an additional polaritonic excitation.

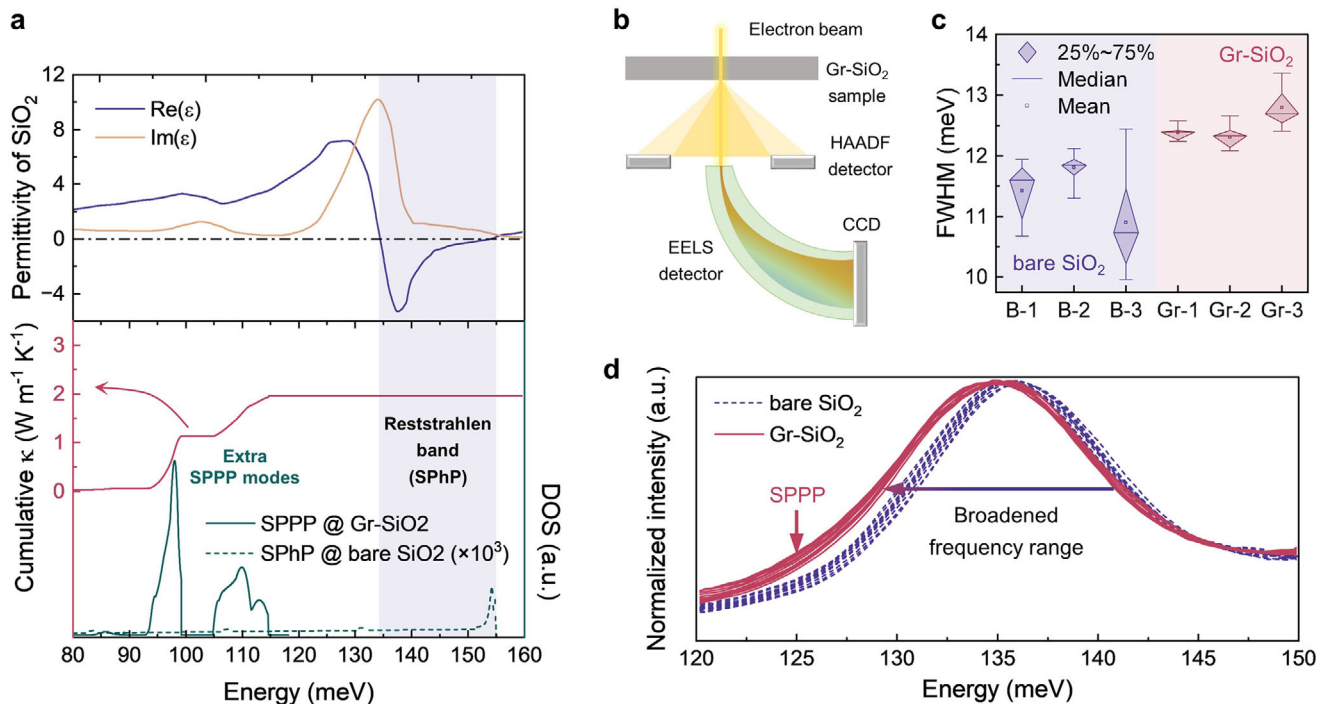


FIGURE 4 | Analytical and experimental evidence of SPPP modes launched at the Gr/SiO₂ interface. (a), DOS of extra SPPP modes excited at the Gr/SiO₂ interface (lower panel), which are absent in the intrinsic Reststrahlen band of SiO₂ as determined by its permittivity (upper panel). The red line in the lower panel shows the contribution to thermal conductivity of SPPs. (b), Schematic illustration of the experimental setup of EELS measurement. (c), Box chart of the measured full widths at half maxima of the characteristic peaks of polaritons in bare SiO₂ (blue) and SiO₂ coated with graphene (red). (d), Measured spectra of polaritons in bare SiO₂ (blue) and SiO₂ coated with graphene (red), showing a frequency-range broadening in the latter structure.

This low-energy spectral broadening in the Gr/SiO₂ sample is consistent with the predicted SPPP modes from our analytical model and s-SNOM examinations (Figure 1c). Thus, our results confirm that while bare SiO₂ supports only conventional SPhPs, the addition of graphene gives rise to hybrid SPPP modes at the interface, serving as potential additional channels for heat transport.

To quantify the contribution of SPPs to heat transport, we calculated the thermal conductivity using the Boltzmann transport equation (BTE) [27]. In the analytical model, SPPs are launched at the Gr/SiO₂ interface according to the calculated DOS (Figure 4a), and then emitted into the adjacent bare SiO₂ region. On the bare SiO₂ segment of the nanoribbon, the launched SPPs exhibit propagation characteristics identical to SPhPs on SiO₂ surfaces, resulting in far longer propagation lengths than plasmon polaritons supported on the surface of metals [56–58], and thus show greater potential as thermal carriers. Given that polaritons in SiO₂ can exhibit propagation lengths on the order of millimeters [28], significantly exceeding the 25 μm length of the SiO₂ beam, it is reasonable to assume that the transport of SPPs is predominantly ballistic. This is reasonable as the total length of the sample becomes a more predominant constraint of the practical propagation length of SPPs over their intrinsic loss (see Note S9). Under this condition, the presence of a graphene layer on SiO₂ results in a significant enhancement in thermal conductivity relative to bare SiO₂. As indicated by the red line in Figure 4a, the calculated increase in thermal conductivity is in close agreement with the trend observed in our

experimental results, supporting the conclusion that the hybrid SPPP modes function as additional thermal energy carriers, making a substantial contribution to the observed enhancement in heat transport.

2.5 | Purcell Intensification of SPPP Modes in FP Nanoresonators

Beyond the excitation of SPPs, the graphene layer patterned with cavity arrays can further enhance thermal transport via FP resonance, owing to its strong reflectivity to surface electromagnetic waves. In this configuration, SPPP waves of specific frequencies undergo constructive interference with waves reflected from the opposite side of the cavity, leading to significant amplification of their intensity. The resonance condition is governed by the m -th order interference criterion:

$$2\text{Re}(q_{sp})W + 2\varphi = 2m\pi \quad (2)$$

where W is the width of the nanoresonators, and φ is the phase shift upon reflection at the graphene interface. Previous studies have determined the reflection-induced phase shift to be approximately $\varphi \approx 0.35\pi$ [39]. Our calculations reveal that only first-order (i.e., $m = 1$) interference is supported under the current conditions, and only for cavity widths of $W = 150$ and 220 nm, as shown in Figure 5a. In contrast, narrower resonators, such as those with $W = 100$ nm, require polaritonic modes with larger wavevectors to satisfy the FP interference condition—making

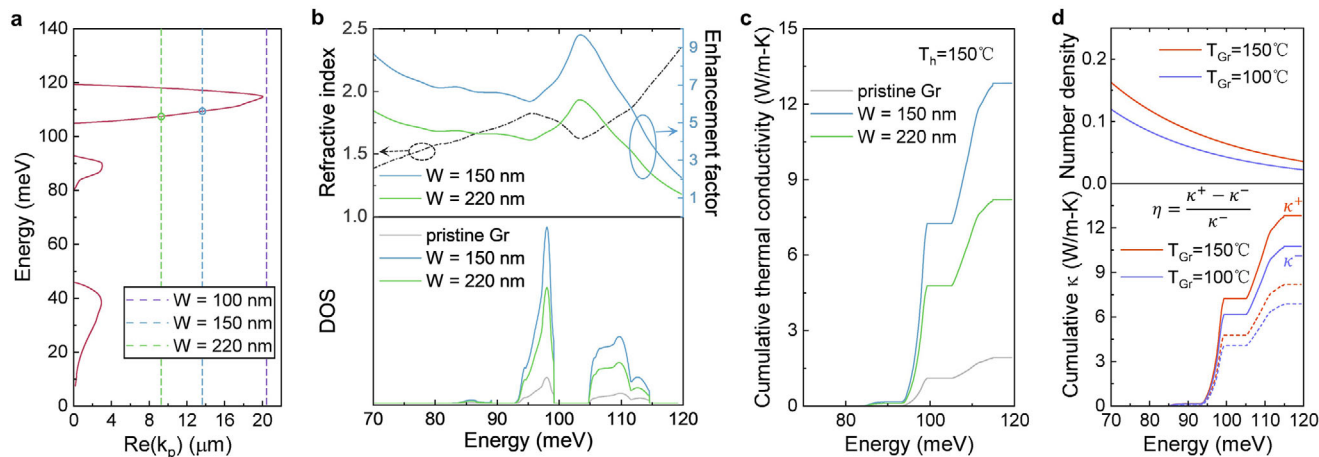


FIGURE 5 | Analysis of thermal conductivity of SiO₂ modulated by graphene nanoresonators. (a), The 1st-order Fabry–Pérot interference condition determined by the dispersion of SPPP and various widths of nanoresonators. (b), The upper panel shows the refractive index of SiO₂ and the DOS enhancement factor caused by FP cavities, and the DOS of SPPP in different structures is demonstrated in the lower panel. (c), Nanoresonator-enhanced cumulative thermal conductivities. (d), Thermal rectification (lower panel) due to various temperatures of the graphene launcher, through exciting different number densities of SPPP (upper panel). The solid and dashed lines in the lower panel represent nanoresonators with $W = 150$ and 220 nm, respectively.

resonant enhancement more difficult to achieve. This explains why the Gr/SiO₂ structure with 100 nm-wide nanoresonators exhibits nearly identical thermal conductivity to the reference sample without resonators (Figure 2c).

By confining SPPP modes into standing waves via interference, the FP nanoresonators effectively compress the electromagnetic wavelength within the cavities to values significantly shorter than those in free space. This spatial confinement leads to a concentrated electromagnetic field distribution, substantially enhancing light-matter interactions. As a result, stronger photon-phonon coupling is achieved, facilitating the excitation of a higher density of SPPs. Such enhancement through FP resonance is analogous to the well-known Purcell effect, first proposed by Purcell to explain increased spontaneous emission rates in optical cavities. This effect has been experimentally demonstrated for surface plasmon polaritons [59] and hyperbolic phonon polaritons [60] using whispering-gallery microcavities. In general, the Purcell effect describes an enhancement of the local electromagnetic density of states (LDOS) by a factor known as the Purcell factor (P), given by

$$P = \frac{3}{4\pi^2} \left(\frac{\lambda}{n} \right)^3 \frac{Q}{V} \quad (3)$$

where λ is the free-space wavelength, n is the refractive index, Q is the cavity quality factor, and V is the mode volume of the resonator, which for FP cavities can be estimated by the physical cavity volume [61]. Unlike emission in free space, the following analysis of the SPPP Purcell effect incorporates its intrinsic two-dimensional confinement (see Note S9).

By accounting for the surface coverage of FP cavities, we estimated the enhancement of the local DOS due to resonance effects. As shown in Figure 5b, the calculated DOS enhancement factor exhibits a clear negative correlation with the refractive index. Notably, the nanoresonators with a width of $W = 150$ nm yield

larger enhancement, attributed to their smaller mode volume, which amplifies the Purcell effect. We further evaluated the thermal conductivity contribution from SPPs based on the BTE [27]. The results, presented in Figure 5c, show that the graphene nanoresonators with W of 150 and 220 nm result in a higher κ compared with pristine graphene, and more importantly, FP resonators with $W = 150$ nm lead to a significantly larger increase in thermal conductivity, consistent with the trend observed in the experiment. This analysis offers a key design guideline: to maximize the thermal conductivity enhancement from SPPs, FP resonators should be patterned as small as possible, while ensuring that the supported SPPP modes still satisfy the interference (resonance) condition.

The thermal-bias-dependent excitation of SPPs in our structure enables effective asymmetric thermal transport under the large temperature gradient. In the ballistic regime described by the BTE, the number density of launched SPPs is determined solely by the temperature of the graphene-coated side. Since this density follows the Bose-Einstein distribution, reversing the heat flow direction alters the SPPP population due to the temperature asymmetry at the launching interface (see Note S9). Under a fixed temperature difference of $\Delta T = 50$ K, consistent with experimental conditions, the calculations reveal a significantly higher SPPP number density when the graphene is placed at a higher temperature. This results in a stronger contribution to thermal conductivity in the forward direction, as shown in Figure 5d. The solid and dashed lines in the lower panel correspond to FP nanoresonators with widths of 150 and 220 nm, respectively, confirming that the thermal rectification is robust across different cavity dimensions. These results demonstrate that the observed thermal rectification originates from the asymmetrical structure design, specifically, the unilateral graphene interface acting as a temperature-sensitive SPPP emitter. The effect arises from the temperature-dependent excitation of additional surface polariton modes, offering a new mechanism for rectifying heat transport via engineered phonon-plasmon interactions.

In this work, we propose a general strategy for modulating thermal transport by harnessing Fabry–Pérot resonances. By integrating graphene nanoresonators as polariton launchers on silica nanobeams, we confine phonon polaritons within small mode volumes, significantly enhancing light-matter coupling and achieving highly tunable and greatly amplified polariton-assisted thermal transport. We further establish an optimization principle for this method: optimizing the thermal conductivity contribution of SPPs necessitates minimizing the Fabry–Pérot resonator's characteristic size, under the constraint that the SPPP mode fulfills the interference criterion. Moreover, we propose a novel active regulation mechanism based on the thermal-bias-governed polaritonic transport. Departing from the prevalent paradigm of asymmetric phonon scattering for thermal rectification, our unilaterally patterned system exploits the temperature-dependent emission characteristics of SPPs to achieve asymmetric thermal transport with a rectification ratio up to 143%. The currently studied silica films are key dielectric materials in integrated circuits. Its asymmetric conduction can actively manage on-chip thermal pathways, improving heat dissipation and safeguarding thermally sensitive components, with applications in opto-thermal co-design. Notably, our strategy circumvents the need to alter the intrinsic lattice structure of the material, offering superior flexibility and reversibility, and broad material compatibility. Furthermore, our nanocavity strategy holds promise for future integration with twisted photonics, where the emergent Moiré superlattice plasmons and twist-angle-dependent topological transitions offer additional degrees of freedom for dynamical manipulation of polariton-mediated heat transfer [62–68]. In summary, we have pioneered a powerful photonic route to manipulate phonon-polariton-mediated thermal conduction, introducing a potent optical dimension to conventional thermal management and expanding the utility of nanophotonics into new territories.

Author Contributions

These authors contributed equally: Siqi Xie, Shuo Qiao. H.W., L.Y. and B.C. conceived and supervised the project. H.W. designed and fabricated the thermal measurement devices. S.X. and H.W. prepared graphene nanoresonators and graphene/SiO₂ heterostructures. S.X., H.W., and H.Z. performed thermal measurements and data analysis. S.X. conducted finite element simulations and performed scattering-type scanning near-field optical microscopy characterization. S.Q. and L.Y. developed the theoretical framework. S.Q. and J.D. performed the electron energy-loss spectroscopy characterization. S.Q. conducted theoretical calculations. The manuscript was drafted by S.X., S.Q., L.Y., and H.W. with input from all authors. All authors discussed the results and contributed to the final paper.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

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

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