Effect of magnetic polaritons in SiC deep grating on radiative transport from far to near field

Yue Yang[‡], Payam Sabbaghi[‡], and Liping Wang^{*}

ABSTRACT

In this work, the effect of magnetic polaritons (MP) inside the SiC grating microstructures on both near- and far-field radiative transport is theoretically studied. Fluctuational electrodynamics that incorporates scattering matrix theory with rigorous coupled-wave analysis is employed to calculate the spectral heat flux between two SiC deep gratings. The results are compared with effective medium theory and proximity approximation method. Besides the well-known coupled surface phonon polaritons (SPhP), MP excited in the grating groove can also cause enhanced spectral heat flux. Confined magnetic field inside the groove of SiC grating, contour plot of transmission coefficient and the prediction by an inductor-capacitor circuit model are used to elucidate the effect of MP. It shows that, compared to the total heat flux between two SiC plates, the one between SiC gratings can be enhanced in far field, while suppressed in near field with small vacuum gap distance. The effects of misalignments, geometrical parameters and vacuum gap distances on both SPhP and MP are investigated as well.

Keywords: magnetic polariton; near-field radiation; inductor-capacitor circuit model; heat flux

1. INTRODUCTION

Near-field radiative heat transfer could be several orders of magnitude greater than that between two blackbodies due to photon tunneling or coupling of evanescent waves [1-3]. The energy transfer can be further improved due to resonance coupling between the emitter and the receiver. Surface plasmon polariton (SPP) is one of the common resonances to enhance radiative heat transfer between metals [4]. However, the metal's plasma frequency usually occurs at very high frequency, where a small part of energy lies at room temperature and the energy transfer enhancement due to SPP coupling is quite limited. Compared to SPP coupling, the surface phonon polariton (SPhP) coupling between polar materials, which occurs around thermal wavelength, holds the potential to significantly increase the radiative heat transfer. Hu et al [5] observed the enhancement effect of SPhP coupling between two closely spaced glass plates via putting the nano spacers between them to generate around 1 μm vacuum gap distance. Later, the same group measured the radiative heat transfer between a glass sphere and a glass plate across nanometer vacuum gaps [6]. The great improvement of near-field radiative transport has also been observed between SiC plates due to strong SPhP coupling [1]. The near-field radiative transport measurements between macroscopic sapphire plates [7] and fused quartz plates [8] were reported as well. In addition, the near-field thermophotovoltaic system performance could be improved by coupling the SPhP of hBN emitter and the SPP of graphene covered InSb cell [9]. Near-field radiation based thermal managements have been recently proposed via applying SPhP coupling between different materials, including thermal rectification [10-12], switching [13, 14], memory [15] and transistor [16].

Excitation of magnetic polaritons (MP) which is due to the strong coupling between electromagnetic waves (photons) and the magnetic resonance plays a significant role in tailoring

far-field radiative properties. It usually requires the structure of metal-insulator-metal to excite MP [17-22]. However, phonon-mediated MP has also been demonstrated in polar materials according to the metallic behavior of these materials in phonon band [23]. A tunable infrared emitter was designed by covering graphene on top of SiC deep grating and exciting MP inside the grating [24]. Applying the phase transition material of vanadium dioxide, the same group also achieved a tunable thermal emitter via MP excitation for both phases [25]. Although phonon-mediated MP has been extensively applied to control far-field radiative properties, its effect on near-field radiative transport has yet to be identified.

In this work, we will theoretically study the excitation of phonon mediated MP in the near-field radiative heat transfer between two SiC gratings microstructures separated by a vacuum gap d . In this study, the radiative heat transfer between two SiC gratings with different vacuum gap distances will be explored. The spectral heat flux, field distribution, contour plot of the energy transmission coefficient and total heat flux as a function of vacuum gap distance will be investigated.

2. THEORETICAL FORMULATION

2.1 Geometry and Radiative Properties of SiC Gratings

As depicted in Fig. 1, the grating period, depth, and ridge width for the reference geometry are denoted as $\Lambda = 5 \mu\text{m}$, $h = 1 \mu\text{m}$, and $w = 4.5 \mu\text{m}$, respectively. The grating filling ratio is then $f = w/\Lambda = 0.9$. The temperatures of emitter and receiver are $T_1 = 400 \text{ K}$ and $T_2 = 300 \text{ K}$, respectively. The scattering formalism [26, 27] that is incorporated into fluctuation electrodynamics with rigorous coupled-wave analysis (RCWA) [28, 29] is employed to exactly calculate the near-field radiative heat flux. The dielectric function of SiC is described by a

Lorentz model [30] as $\varepsilon_{\text{SiC}}(\nu) = \varepsilon_{\infty} \left(1 + \frac{\nu_{\text{LO}}^2 - \nu_{\text{TO}}^2}{\nu_{\text{TO}}^2 - i\gamma\nu - \nu^2}\right)$, where ν is the frequency in wavenumber, the high-frequency constant ε_{∞} is 6.7, the longitudinal optical-phonon frequency ν_{LO} is 969 cm^{-1} , the transverse optical-phonon frequency ν_{TO} is 793 cm^{-1} , and scattering rate γ equals 4.76 cm^{-1} at room temperature.

2.2 Fluctuational Electrodynamics Coupled with Scattering Matrix Method

Near-field spectral radiative heat transfer between two gratings based on the exact scattering theory is expressed as [26, 27, 31]

$$q_{\omega} = \frac{1}{2\pi^3} \left[\Theta(\omega, T_1) - \Theta(\omega, T_2) \right] \int_0^{\pi/\Lambda} \int_0^{\infty} \xi(\omega, k_{x0}, k_y) dk_y dk_{x0} \quad (1)$$

where $\Theta(\omega, T) = \hbar\omega / (e^{\hbar\omega/k_B T} - 1)$ is average energy of Planck's oscillator, ω is angular frequency, and k_{x0} and k_y are the incident wavevector components in x and y direction, respectively. The energy transmission coefficient $\xi(\omega, k_{x0}, k_y)$, that depends on the frequency and wave vector components is given as [32]

$$\xi(\omega, k_{x0}, k_y) = \text{tr}(\mathbf{D}\mathbf{W}_1\mathbf{D}^{\dagger}\mathbf{W}_2) \quad (2a)$$

$$\mathbf{D} = (\mathbf{I} - \mathbf{S}_1\mathbf{S}_2)^{-1} \quad (2b)$$

$$\mathbf{W}_1 = \Sigma_{-1}^{pw} - \mathbf{S}_1 \Sigma_{-1}^{pw} \mathbf{S}_1^{\text{rf}} + \mathbf{S}_1 \Sigma_{-1}^{ew} - \Sigma_{-1}^{ew} \mathbf{S}_1 \quad (2c)$$

$$\mathbf{W}_2 = \Sigma_1^{pw} - \mathbf{S}_2 \Sigma_1^{\text{rf}} \mathbf{S}_2^{pw} + \mathbf{S}_2 \Sigma_1^{ew} - \Sigma_1^{ew} \mathbf{S}_2 \quad (2d)$$

where $\mathbf{S}_1 = \mathbf{R}_1$ and $\mathbf{S}_2 = e^{ik_{z0}d} \mathbf{R}_2 e^{ik_{z0}d}$. $\mathbf{R}_1$ and $\mathbf{R}_2$ are the reflection matrixes obtained by using

RCWA method [27-29]. The operators $\Sigma_n^{pw/ew} = \frac{1}{2} k_z^n \Pi^{pw/ew}$, where $\Pi^{pw/ew}$ are the projectors on

the propagative and evanescent waves, were clearly defined previously [27]. According to the

Bloch wave conditions, the in-plane wavevector on the interface between grating and vacuum can be expressed as

$$k_{\square,j} = \sqrt{(k_{x0} + \frac{2\pi}{\Lambda}j)^2 + k_y^2} \quad (3)$$

where j ($= 0, \pm 1, \pm 2, \dots$) refers to different diffraction order.

To ensure the numerical accuracy of the calculation with reasonable computational time for the reference geometry, a total of 101 angular frequency values evenly spanned from 1.4×10^{14} rad/s to 1.9×10^{14} rad/s within the phonon absorption band of SiC was considered, while 40 and 120 data points were used for k_{x0} and k_y accordingly for calculating the spectral heat flux at each frequency after double integrations. The upper limit of k_y was set as $10\omega/c$, and then it will reduce to a cutoff value, above which the transmission coefficient is smaller than 0.5% of the maximum value when $k_{x0} = 0$. For a given frequency, the maximum diffraction order was iterated by adding 5 orders each time until the relative error between consecutive calculations is smaller than 1%. It turned out that a total of 101 diffraction orders were required to ensure the numerical convergence.

2.3 Effective Medium Theory

Local effective medium theory (EMT) is also used to obtain the anisotropic dielectric function by homogenizing the grating layer as a uniaxial thin film [33]. This method is usually valid when the grating dimension is much smaller than the characteristic wavelength. Applying the Maxwell-Garnett theory, the effective dielectric functions can be expressed as [33]

$$\varepsilon_o = 1 - f + \varepsilon_{\text{SiC}} f \quad (4)$$

$$\varepsilon_E = \frac{\varepsilon_{\text{SiC}}}{(1 - f)\varepsilon_{\text{SiC}} + f} \quad (5)$$

where the subscript “O” and “E” denote the ordinary and extraordinary component of dielectric function, respectively. As the optical axis of considered grating structure is along x axis shown in Fig. 1, it gives $\varepsilon_{xx} = \varepsilon_E$, and $\varepsilon_{yy} = \varepsilon_{zz} = \varepsilon_O$. The real parts of the dielectric function in orthogonal directions ε_O and ε_E of SiC gratings calculated by Eqs. (4) and (5) are shown in Fig. 2. As presented in a shaded region of Fig. 2 from $\omega = 1.5 \times 10^{14}$ to 1.64×10^{14} rad/s, the real part of ε_E is positive, while that of ε_O is negative, which indicates a region with type II hyperbolic behavior. Note that there is a singularity point when frequency is around 1.5×10^{14} and 1.65×10^{14} rad/s, for real part of ε_O and ε_E , respectively. These behaviors are called epsilon near pole (ENP), which may cause enhanced absorption.

2.4 Derjaguin’s Proximity Approximation

On the other hand, the Derjaguin’s proximity approximation (PA) method, which considers a weighted heat transfer between plates, is investigated as well. Therefore, the PA method can only consider the SPP/SPhP coupling between two planar surfaces. For one dimensional grating with $f = 0.9$ and no lateral shift, the radiative heat flux can be predicted by PA as [32]

$$q_{\omega}^{\text{PA}} = f \times q_{\omega}^{\text{plate}}(d) + (1-f) \times q_{\omega}^{\text{plate}}(d+2h) \quad (6)$$

where $q_{\omega}^{\text{plate}}(d)$ and $q_{\omega}^{\text{plate}}(d+2h)$ are the spectral heat fluxes between two plates at a gap distance of d and $d+2h$, respectively.

3. RESULTS AND DISCUSSION

3.1 Spectral Heat Flux

In Fig. 3, the spectral radiative heat fluxes between two SiC gratings predicted by rigorous scattering matrix method (denoted as Grating case), EMT and PA method are compared with planar surfaces and far-field blackbody limitation. Note that the default grating parameters are used and the vacuum gap distance is $d = 1 \text{ } \mu\text{m}$. For the planar case, a significantly enhanced spectral heat flux around $1.79 \times 10^{14} \text{ rad/s}$ has been observed, which is well known as the strong SPhP coupling between SiC plates in near field. Unlike the planar case, besides the enhanced spectral heat flux around $1.79 \times 10^{14} \text{ rad/s}$ due to strong SPhP coupling, there are two additional peaks at frequencies around $\omega = 1.61 \times 10^{14} \text{ rad/s}$ and $\omega = 1.75 \times 10^{14} \text{ rad/s}$ for the grating case. In order to explore the underlying mechanism for these additional peaks, the spectral heat fluxes between SiC gratings calculated by EMT and PA method are investigated. The PA method predicts almost the same spectral heat flux with planar case, which is because it is an approximate method to consider the weighted sum of planar contributions and the filling ratio is as large as 0.9.

The spectral heat flux between two SiC gratings calculated by EMT method can be obtained by setting up the diffraction order in the rigorous scattering matrix theory as 0, i.e.

$$q_{\omega}^{\text{EMT}} = q_{\omega}(N = 0) \quad (7)$$

where q_{ω} is expressed in Eq. (1), and N is the diffraction order used to calculate the reflection coefficient through RCWA. Note that by setting up $N = 0$, the k_{x0} range shown in Eq. (1) cannot be limited by π/Λ anymore and a sufficiently large one should be provided. As predicted by the EMT method, besides the spectral heat flux peak due to SPhP coupling similar to planar case, another broadband enhancement from 1.54×10^{14} to $1.59 \times 10^{14} \text{ rad/s}$, and an additional peak around $1.63 \times 10^{14} \text{ rad/s}$ have been observed. Compared with the effective medium dielectric functions shown in Fig. 2, it is easy to identify that the broadband enhancement is due to the

hyperbolic behavior and the additional peak comes from ENP mode. Although additional spectral heat flux peaks are predicted by the EMT method, the frequencies are not consistent with the ones calculated by rigorous scattering matrix theory. Therefore, the PA method under predicts the spectral heat flux between two SiC gratings, while the EMT method over predicts it.

Since the two additional peaks of the spectral heat flux between two SiC gratings are consistent with the MP resonance frequencies corresponding to the far-field spectral emittance peaks of the same SiC grating geometry studied in Ref. [23], this suggests that these two spectral heat flux peaks may be due to MP excitation. Therefore, in order to verify this, the LC circuit model result of far-field SiC grating and contour plot of energy transmission coefficient along with magnetic field distribution at spectral peak frequencies will be presented as follows.

3.2 Exploration of Underlying Mechanism

In order to confirm that MP resonance exists in near field and the spectral heat flux peaks at $\omega = 1.61 \times 10^{14}$ rad/s and $\omega = 1.75 \times 10^{14}$ rad/s are due to MP resonance, the contour plots of energy transmission coefficient at $d = 1 \text{ }\mu\text{m}$ for two SiC gratings and planar surfaces are shown in Fig. 4(a) and 4(b), respectively. Note that $0 < k_{x0} < \pi/\Lambda$ and $k_y = 0$ is specified, and k_{x0} is normalized to the light line with $\omega_0 = 1.5 \times 10^{14}$ rad/s. The brightness in the figure indicates the strength of energy transmission across the vacuum gap in the near field. The dispersion curves for SPhP coupling between SiC plates are also presented as white dash lines by solving the following equation [1]

$$\frac{k_{1z}}{\varepsilon_1} + \frac{k_{0z}}{\varepsilon_0} \coth\left(\frac{k_{0z}d}{2i}\right) = 0 \quad (8)$$

where the subscript “1” and “0” refers to SiC and vacuum, respectively. k_z is the wavevector component vertical to the interface. The good agreement of the coupled-SPhP dispersion curve

calculated by equation (8) and transmission coefficient enhancement band confirms that strong horizontal enhancement band at $\omega_{\text{SPhP}} = 1.79 \times 10^{14}$ rad/s is due to SPhP coupling between SiC.

As shown in Fig. 4(a), there are two more strong horizontal enhancement bands for grating structure at $\omega_{\text{MP1}} = 1.61 \times 10^{14}$ rad/s and $\omega_{\text{MP2}} = 1.75 \times 10^{14}$ rad/s, which are independent of wavevector k_{x0} . The interaction between them and coupled-SPhP have changed the behavior of coupled-SPhP modes. The independency of these two enhancement bands on wavevector k_{x0} is consistent with the characteristic of MP resonance investigated in far field [18, 20, 23].

The far-field MP resonance frequency can be predicted using LC circuit model by zeroing the total impedance [23]

$$Z_{\text{tot}} = i\omega(L_m + L_k - \frac{1}{\omega^2 C}) = 0 \quad (9)$$

where L_m , L_k , C are respectively mutual inductor, kinetic inductor, and capacitor, whose expressions can be found in Ref. [23]. Using Eq. (9), the resonance angular frequency is predicted to be $\omega_{\text{LC}} = 1.61 \times 10^{14}$ rad/s by the LC circuit model (shown as green triangles), which matches very well with the horizontal enhancement band of transmission coefficient around ω_{MP1} from the rigorous solution. This clearly confirms the excitation of MP and its enhancement on heat transfer in near field. By comparison between the spectral heat fluxes at $d = 1 \mu\text{m}$, it can be observed that $\omega_{\text{MP2}} = 1.75 \times 10^{14}$ rad/s also occur at the same resonance frequency in both far and near fields, suggesting that the spectral enhancement in near-field radiative transfer at $d = 1 \mu\text{m}$ is associated with the excitation of MP.

To further understand the physical mechanism, we look into the magnetic field distribution and the schematic of a simulation case to calculate magnetic field at MP and SPhP resonance frequencies for two SiC gratings is shown in Fig. 5(a). Boundary conditions are set as

perfectly matched layers (PML). Moreover, due to the dominant contributions of p-polarized waves, electric dipole sources located in the SiC emitter are considered to oscillate only in X and Z direction and their corresponding magnetic fields are summed up incoherently. As shown in Fig. 5(a), the distance of electric dipole sources with their neighbors and also with the surface of SiC emitter is set as $0.1\mu\text{m}$. The corresponding magnetic field at MP and SPhP resonance frequencies calculated by FDTD is respectively shown in Fig. 5(b) and 5(c). As shown in Fig. 5(b), at MP resonance frequency, the radiative flux can be spectrally enhanced due to confined magnetic field inside the grooves of SiC grating, which is consistent with the MP behavior studied before [23]. However, at coupled-SPhP resonance frequency shown in Fig. 5(c), the magnetic field transports along the interface between the vacuum and SiC surface, which is also exactly the behavior associated with surface waves.

3.3 Geometry Effects on MP

To further confirm and understand the behaviors of MP resonance in near-field radiative transport across vacuum gaps, the grating geometric effect on near-field radiative transfer between SiC gratings is investigated in terms of transmission coefficient at the gap distance $d = 1\mu\text{m}$. Figures 6(b), 6(c) and 6(d) respectively present the effect of groove width (b), grating depth (h) and grating period (Λ) on the resonance respectively in comparison to the default case shown in Fig. 6(a). The MP resonance frequencies predicted by the LC circuit model are also presented as green triangles in the figure, and they match very well with the horizontal enhancement bands for each case.

When increasing the groove width from $0.5\mu\text{m}$ to $1\mu\text{m}$, the MP1 resonance shifts to a higher frequency by comparing Fig. 6(a) and (b), which is due to the effect of the change of both

inductors and capacitors. Similarly, through the comparison between Fig. 6(a) and (c), when grating depth decreases from 1 μm to 0.5 μm , the MP resonance will increase to a higher frequency. However, the change of grating period can hardly change the MP resonance as illustrated in Fig. 6(a) and (d). This is due to that the energy penetration depth in SiC is much smaller than the grating width and the grating period has little effect on any inductor or capacitor.

The spectral heat fluxes between two SiC gratings with different geometries are also investigated in Fig. 7. Consistent with the behavior explained in Fig. 6, as groove width increases or grating depth decreases, the spectral heat flux peak associated with MP1 will shift to a higher frequency, while the grating period change cannot shift the position. The MP2 resonance frequency stays to be unchanged, which is consistent with previous observations in far field.

3.4 Effect of Lateral Displacement

The lateral displacement effect on spectral heat flux between two SiC gratings is also investigated. For the reference geometry with default parameters, the spectral heat fluxes for three different lateral displacements are shown in Fig. 8 with $d = 1 \mu\text{m}$. As lateral displacement increases from perfect alignment, MP1 resonance frequency shifts to higher values while that for MP2 and coupled-SPhP frequency is not changing.

The corresponding magnetic fields at MP and SPhP resonance frequencies for $\delta = 0.25\lambda$ and $\delta = 0.5\lambda$ are also shown in Fig. 9. Similar to the perfect alignment case shown in Fig. 5, magnetic fields are confined within the grating groove to cause enhanced spectral heat flux at MP resonance. At coupled-SPhP resonance frequency, the surface waves just propagate along the interface between the vacuum gap and SiC grating as expected.

3.5 Vacuum Gap Effect

Figure 10 shows the spectral radiative heat fluxes between SiC gratings at several different vacuum gap distances for both near-field and far-field regimes. For $d = 1 \text{ }\mu\text{m}$, different from the case of two SiC plates, the broadband peak around $\omega_{\text{MP1}} = 1.61 \times 10^{14} \text{ rad/s}$ and a small peak around $\omega_{\text{MP2}} = 1.75 \times 10^{14} \text{ rad/s}$ only occur between two SiC gratings, which could enhance the radiative heat transfer. These two additional peaks have been already explained as the excitation of MP inside the groove of grating structures. When the vacuum gap increases to $5 \text{ }\mu\text{m}$, an enhanced spectral heat flux due to MP1 can still be observed, and the amplitude doesn't change much. However, the spectral heat flux peak due to coupled-SPhP will drop significantly because of a much weaker coupling with a larger vacuum gap. Different from the case of $d = 1 \text{ }\mu\text{m}$, where coupled-SPhP dominates the total heat transfer, MP1 and coupled-SPhP have the equivalent effect at $d = 5 \text{ }\mu\text{m}$. As the vacuum gap further increases to $10 \text{ }\mu\text{m}$, the enhanced spectral heat flux due to coupled-SPhP further decreases and that due to MP1 still doesn't change much, which results in that MP1 will dominate the total heat transfer.

On the other hand, when the vacuum gap distance becomes below $1 \text{ }\mu\text{m}$, the spectral heat fluxes between two SiC gratings and two SiC plates are shown in Fig. 10(b). For the case of $d = 500 \text{ nm}$, similar to that at $d = 1 \text{ }\mu\text{m}$, the enhanced spectral heat flux due to MP1 and MP2 can still be observed, and coupled-SPhP between gratings is the same with plates. However, when the vacuum gap further decreases to 100 nm , the effect of MP on enhancing spectral heat flux can hardly be seen, which is due to that at smaller vacuum gap the evanescent waves tunneling may dominate the heat transfer other than MP around the frequency of $1.62 \times 10^{14} \text{ rad/s}$. At an extremely small vacuum gap of $d = 10 \text{ nm}$, the low-frequency branch of coupled-SPhP will shift to a lower frequency and may have strong interaction with MP1. The consequent result is that compared to the case of two SiC plates, the spectral heat flux due to coupled-SPhP will drop and

MP1 will shift to a lower frequency to cause an enhanced spectral heat flux around 1.55×10^{14} rad/s as shown in Fig. 10(b).

The total radiative heat fluxes between two SiC gratings calculated by rigorous scattering theory, EMT and PA method along with the results of SiC plates are shown in Fig. 11. It can be noted that when vacuum gap is larger than 1 μm , there is an enhancement in total heat flux of grating structures in comparison to planar case, which is due to the excitation of MP. Although EMT method can follow the same trend with rigorous scattering theory, this is coincidence because the total heat transfer enhancement for EMT method is mainly from hyperbolic and ENP behavior explained in Fig. 3. When the vacuum gap distance is smaller than 1 μm , because of the dominating effect of coupled-SPhP and evanescent waves tunneling, the total heat flux between SiC gratings is similar to that between SiC plates. However, when vacuum gap becomes below 20 nm, the total heat flux for grating is becoming less than planar SiC plates due to the interaction of MP and coupled-SPhP, which causes a significant decrease of spectral heat flux at coupled-SPhP frequency as shown in Fig. 10(b). Neither EMT nor PA method can predict the total heat flux decrease below 20-nm vacuum gap. For vacuum gap below 1 μm , the function between the total heat flux and the vacuum gap distance is fitted, and it shows that the total heat flux is proportional to d^2 and $d^{1.7}$ for SiC plates and SiC gratings accordingly.

4. CONCLUSION

In summary, we have theoretically investigated for the first time the effect of magnetic polaritons excited inside the deep groove of SiC grating microstructures on both near- and far-field radiative transport. It shows that at larger vacuum gap distance in far field, compared to the

case of SiC plates, SiC gratings have a higher total heat flux due to MP excitation. However, when it comes to near field with small vacuum gap distance, MP can hardly improve the total heat flux due to the dominating coupled-SPhP effect and even suppress it after interaction with coupled-SPhP at extremely small vacuum gap. The EMT and PA methods are also analyzed and neither of them can predict the heat transfer correctly. The contour plots of transmission coefficient and magnetic field distribution have been employed to identify the MP effect as well. The understanding gained here will undoubtedly benefit the spectral control of near-field thermal radiation with magnetic polaritons for energy-harvesting applications like thermophotovoltaic energy conversion and radiation-based thermal management.

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Figure Captions:

- Fig. 1 Schematic of radiative heat transfer between two symmetric SiC deep gratings with the grating parameters of period (Λ), depth (h), groove width (b) and ridge width (w). The emitter and receiver temperatures are respectively set as $T_1 = 400$ K, and $T_2 = 300$ K in this study. The vacuum gap distance is denoted as d .
- Fig. 2 Effective dielectric functions (real part only) for SiC gratings with $f = 0.9$. The hyperbolic dispersion is supported in a narrow band between 1.5×10^{14} and 1.64×10^{14} rad/s as shown by the shaded regions.
- Fig. 3 Spectral heat fluxes between two aligned SiC gratings at $d = 1$ μm calculated from RCWA, EMT and PA method. The spectral heat flux between two SiC plates at $d = 1$ μm , and far-field blackbody limit are also presented. The grating geometry is set as the default.
- Fig. 4 Contour plot of energy transmission coefficient (ξ) between (a) two symmetric SiC gratings at vacuum gap of 1 μm with default values and (b) two SiC plates at vacuum gap of 1 μm . Note that $k_y = 0$ is assumed in this plot and k_{x0} is normalized ($\omega_0 = 1.5 \times 10^{14}$ rad/s). The dispersion relations for coupled SPhP between two SiC plates at $d = 1$ μm are plotted as the white dash lines and the MP resonance frequencies predicted by LC circuit model are also shown with green triangles.
- Fig. 5 (a) Schematic of the case to apply electric dipoles to simulate magnetic field of p-polarized waves between two SiC gratings at MP and SPhP resonance frequencies in FDTD software. Contour plot of magnetic field between two symmetric SiC gratings at (b) magnetic polariton resonance frequency and (c) SPhP resonance frequency at $d = 1$ μm when geometric parameters are set at default values.
- Fig. 6 Contour plot of transmission coefficient (ξ) between two symmetric SiC gratings with different geometries of (a) $\Lambda = 5$ μm , $h = 1$ μm , $b = 0.5$ μm ; (b) $\Lambda = 5$ μm , $h = 1$ μm , $b = 1$ μm ; (c) $\Lambda = 5$ μm , $h = 0.5$ μm , $b = 0.5$ μm ; (d) $\Lambda = 2.5$ μm , $h = 1$ μm , $b = 0.5$ μm . Note that vacuum gap distance are assumed as 1 μm for all cases.

- Fig. 7 Spectral heat fluxes between two aligned SiC gratings at $d = 1 \text{ } \mu\text{m}$ for different geometries.
- Fig. 8 Spectral heat fluxes between two SiC gratings at $d = 1 \text{ } \mu\text{m}$ calculated for three different lateral displacement.
- Fig. 9 Contour plot of magnetic field between two symmetric SiC gratings at (a) magnetic polariton resonance frequency and (b) SPhP resonance frequency for $\delta = 0.25\lambda$ and (c) magnetic polariton resonance frequency and (d) SPhP resonance frequency for $\delta = 0.5\lambda$ when $d = 1 \text{ } \mu\text{m}$ and other geometric parameters are set at default values.
- Fig. 10 Spectral heat fluxes between two SiC gratings at different vacuum gaps in both (a) far-field regime and (b) near-field regime. The spectral heat fluxes between two SiC plates for blackbody limit are also presented. The emitter and receiver temperatures are set as 400 K and 300 K, respectively. The grating parameters are set as the default values.
- Fig. 11 Total heat fluxes between two SiC gratings at different vacuum gaps calculated by all rigorous scattering theory, EMT and PA method. The total heat flux between two SiC plates at different vacuum gaps is also presented. The emitter and receiver temperatures are set as 400 K and 300 K, respectively. The grating parameters are set as the default values.

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