Thermal emission and absorption of radiation in finite inverted-opal photonic crystals

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We study theoretically the optical properties of a finite inverted-opal photonic crystal. The light-matter interaction is strongly affected by the presence of the three-dimensional photonic crystal and the alterations of the light emission and absorption processes can be used to suppress or enhance the thermal emissivity and absorptivity of the dielectric structure. We investigate the influence of the absorption present in the system on the relevant band edge frequencies that control the optical response of the photonic crystal. Our study reveals that the absorption processes cause spectral broadening and shifting of the band edge optical resonances, and determine a strong reduction of the photonic band gap spectral range. Using the angular and spectral dependence of the band edge frequencies for stop bands along different directions, we argue that by matching the blackbody emission spectrum peak with a prescribed maximum of the absorption coefficient, it is possible to achieve an angle-sensitive enhancement of the thermal emission/absorption of radiation. This result opens a way to realize a frequency-sensitive and angle-sensitive photonic crystal absorbers/emitters.

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I. INTRODUCTION

Photonic crystals and in particular photonic band gap (PBG) materials constitute a class of dielectric materials in which the basic electromagnetic interaction is controllably altered over certain frequencies and length scales [1–5]. The ability to tailor the optical properties in a prescribed manner and the specific symmetry properties of the electromagnetic field inside a PBG are the fundamental instruments at our disposal to design materials and devices that control the emission and absorption properties of light. In the context of quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics, the radiation reservoir associated with a photonic crystal presents drastic departures from the ordinary quantum optics. Photonic crystals and in particular photonic band gap materials constitute a class of dielectric materials in which the basic electromagnetic interaction is controllably altered over certain frequencies and length scales [1–5]. The ability to tailor the optical properties in a prescribed manner and the specific symmetry properties of the electromagnetic field inside a PBG are the fundamental instruments at our disposal to design materials and devices that control the emission and absorption properties of light.
shifting of the band edge optical resonances and determine a
strong reduction of the photonic band gap spectral range, and
that the finite size character of the photonic crystal sample
leads to a stronger dependence these optical response on
the propagation direction of the incident radiation. We also
evaluate the spectral and angular dependence of the thermal
response of the inverted opal structure. The exact knowledge
of the angular and spectral dependence of the band edge
frequencies can be used to match the blackbody emission
spectrum peak with a prescribed maximum of the absorption
coefficient. Thus, it is possible to achieve an angle-sensitive
enhancement of the thermal emission/absorption of radiation.
This result may open a way to realize frequency-sensitive
and angle-sensitive photonic crystal absorbers/emitters,
which may find applications in thermovoltaic energy conver-
sion devices [23].

This paper is organized as follows. In Sec. II, we intro-
duce the physical system we investigate and present a brief
review of the theoretical formalism and numerical approach
we use. In Sec. III, we analyze the optical (transmission and
absorption coefficients) and thermal (absolute thermal power
spectrum) response of a finite inverted opal photonic crystal
in different configurations. In Sec. III A, we calculate the
transmission spectrum for nonabsorbing inverted opal struc-
tures, while in Sec. III B we calculate the absorption and
thermal power spectra for an inverted opal structure that con-
tains an absorptive material. In Sec. III C, we consider a
different configuration, in which the photonic crystal struc-
ture is used as passive filter against the thermal radiation
emitted by a highly absorptive substrate. In Sec. IV, we dis-
cuss the results of the study presented in this paper.

II. MODEL AND THEORETICAL FRAMEWORK

We model the three-dimensional photonic crystal as a fi-
nite inverted opal structure. Inverted opal photonic crystals
are ideal for high-quality, large scale fabrication of photonic
band gap materials with band gaps at micron or submicron
wavelengths [24,25]. The existence of natural opals (a na-
tural photonic crystal consisting of spherical “particles” sitting
on a fcc lattice) suggested that similar artificial microstruc-
tures can be fabricated through colloidal self-assembly. The
threshold for the index of refraction contrast required to ob-
tain a full photonic band gap in opal structures is 2.8, and the
opening of the gap is favored in inverted structures, i.e.,
structures in which the fcc spheres are made out of low-index
of refraction dielectric material, while the background mate-
rial presents a high index of refraction. The fabrication pro-
cedure [25], while presenting numerous experimental chal-
cenges, is principally straightforward. The initial structure,
usually a close-packed face centered cubic lattice of SiO2
spheres (direct opal), is infiltrated with high reflective index
material such as Si or Ge and subsequently the original SiO2
dielectric material is removed by chemical etching. Theoreti-
cal and experimental studies have shown that depending on
the degree of infiltration, PBG materials with band gaps in
the range of 5%–15% of the central frequency can be real-
ized [18].

In our study, we consider a fully infiltrated inverted opal
structure made out of silicon (εSi=11.9). Such a structure

FIG. 1. (Color online) Band structure and corresponding density
of states (DOS) for a close-packed fcc cubic lattice of air spheres in
silicon (εSi=11.9) (see also Ref. [18]).

consists of close-packed fcc cubic lattice of air spheres in a
high index of refraction dielectric background. In the ab-
sence of absorption and for an infinite periodic structure, the
band structure and density of modes calculations reveal a
relatively broad photonic band gap between the eighth and
ninth bands, centered around the frequency \( \omega_c=0.87\omega_0 \) with
a band gap width of 4.25% of the central frequency (Fig. 1)
(see also Ref. [18]). For this crystal structure, we compute the
transmission and the reflection coefficients of the crystal,
\( T \) and \( R \), respectively, as a function of the frequency \( \omega \) and
the wave vector \( k \) of the incident wave. For a crystal with
real indices of refraction (no absorption or gain), the conserv-
ation of the energy requires \( R=T=1 \). On the other hand, in
the presence of absorption (corresponding to a complex in-
dex of refraction), there will be a nonzero absorption coeffi-
cient and conservation of energy requires \( A=1-R-T \). Moreover, Kirchoff’s second law states that a material’s ther-
mal emittance \( E \) is proportional to its absorbance—and that
the emittance is equal to its absorbance for a perfect black-
body thermal element. In this case, we have

\[
E_k(\omega) = A_k(\omega) = 1 - [R_k(\omega) + T_k(\omega)],
\]

where \( E_k(\omega) \) is the ratio of the thermal optical power (Poyn-
ing’s vector) emitted at the frequency \( \omega \) into a spherical-
angle element \( d\Omega_k \) by a unit surface area perpendicular on \( k \),
to the power emitted by a blackbody at the same tempera-
ture, \( T \). Then, the emittance can be obtained by simply mul-
tiplying Planck’s blackbody power spectrum by the absorp-
tion coefficient [15]

\[
E_k(\omega,T) = E_k(\omega) \frac{\omega^2}{2\varepsilon c} 
\frac{\hbar \omega}{e^{\hbar \omega/kT} - 1}.
\]

As pointed out previously [15], and explicitly proved by nu-
merical simulations of one-dimensional [27] and two-
dimensional photonic crystals [28], this “indirect” method of
evaluating the emittance is equivalent to the direct method
that involves a quantum mechanical evaluation of the power
spectrum of the elementary absorbers/emitters interacting
with the photonic reservoir of modes of the periodic dielec-
tric structure.
In evaluating the transmission, reflection and absorption coefficients for the finite inverted opal structure, we employ the numerical formalism developed in Refs. [26,29]. Based on the transfer matrix method (TMM) and on-shell techniques, the formalism is highly efficient and accurate in evaluating the optical properties of a multilayer sequence of spherical particles embedded in a homogeneous dielectric host. The principle of TMM is straightforward: the total dielectric structure is divided into small cells and the associated complex transmittance and reflectance \( r \) and \( t \), respectively, for a given cell are evaluated. Then the fields in each cell are coupled to those of neighboring cells, and the total transfer matrix is relating the incident electric fields on the left side of the structure to the outgoing fields on the right side. The method also allows for the computation of the band structure of an infinite structure, but its major advantage is that it allows the evaluation of the transmission, reflection and absorption coefficients for fields incident on finite-thickness slabs of photonic crystal. For example, in a one-dimensional case, the \( T \) and \( R \) are equal to \(|t|^2\) and \(|r|^2\), respectively, where \( r \) and \( r \) are the complex transmittance and reflectance coefficients, respectively. These coefficients are linearly related to one another by a \( 2 \times 2 \) matrix \( \hat{M} \), according to

\[
\begin{bmatrix}
1 \\
r
\end{bmatrix} = \hat{M} \begin{bmatrix}
t \\
0
\end{bmatrix},
\]

where

\[
\hat{M} = \begin{bmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{bmatrix}.
\]

The column vectors on each side of Eq. (3) represent the fields outside each side of the crystal. Then \( t = 1/M_{11} \) and \( r = M_{21}/M_{11} \). This matrix \( \hat{M} \) can be constructed for a one-dimensional structure simply by multiplying the transfer matrices for the individual layers. For a homogeneous plate, these individual layer transfer matrices can be readily computed by taking into account the reflection and transmission at the interface at the edges of the plate with the Fresnel equations, along with the accumulated phase (and possible change in amplitude, if the index of refraction has an imaginary component) from propagating through the material. Because the phase accumulated from the wave propagating through a given layer depends on the portion of the wave vector that is perpendicular to the interfaces of the plates, the frequency \( \omega \) at which the gap is centered is highly dependent on the angle of incidence of the initial radiation.

The on-shell method used by a Stefanou and co-workers [26,29] allows the evaluation of the optical response of finite number of parallel planes of spheres of differing index of refraction from the host material in which they are embedded. For a given frequency \( \omega \), the incident plane wave is expanded into spherical waves about an origin centered at one sphere, and then the scattered wave from a single sphere in one plane is calculated by satisfying the boundary conditions for Maxwell’s equations at the surface of a single sphere. The scattered wave for the entire infinite plane of spheres is just the sum of the scattered waves for a single sphere expanded about a translated origin, with a phase factor corresponding to the portion of the incident wave vector that is parallel to the plane of spheres. By summing this first-order scattering of all the spheres, except the sphere at the origin, and then expanding the result into spherical waves about the origin, we can obtain a better approximation of the wave that is incident on the sphere at the origin. Here, the restriction that each plane of spheres has the same two-dimensional periodicity implies that the cumbersome spherical wave expansion is calculated only once per frequency, which makes this method much more numerically feasible than other approaches. By solving the boundary conditions again, with the spherical wave expansion of the incident plane wave plus this first order scattered wave, we solve for a second-order scattering of the sphere at the origin. By symmetry, all the spheres of the infinite plane have this same scattered wave. Hence, the total scattered wave for the plane is again the sum of the scattered waves for a single sphere, expanded about a translated origin, with a phase factor. The end result is then expanded into plane waves and added to the incident wave to solve for the total transmitted and reflected field. By repeating this procedure for each plane of spheres, the total field for the entire crystal is obtained.

The multiple scattering techniques and the TMM which constitute the basis of the numerical algorithms used are extremely accurate and highly efficient means to characterize the optical response of the structure considered, since the scattering matrix of each sphere can be obtained analytically. Moreover, the TMM approach is conceptually much simpler than the traditional quantum electrodynamics method of solving the nontrivial boundary conditions involved, and also not nearly as computationally intensive as the finite difference time domain (FDTD) simulations. This technique also takes into account the essentially finite nature of the structure, crucial for experimental work where often it is possible to fabricate only a few layers of crystal, and it is often necessary to account for the inherent presence of absorption that characterizes many of the dielectric materials that the photonic crystal samples are made out of.

III. NUMERICAL RESULTS

Our goal is to evaluate the emissivity of three-dimensional inverted opal photonic crystal and investigate its dependence on the angle of the incident radiation.

As depicted in Fig. 2, the fcc crystal (lattice constant \( a \)) grown along the \([111]\) direction is modeled as a sequence \( \ldots \) ABCABC \( \ldots \) of parallel planes of dielectric spheres of radius \( r \) and high-dielectric constant \( \varepsilon_2 \) embedded in low-dielectric constant medium (\( \varepsilon_1 \)). The individual layers of spheres A, B, C have the same periodicity in \( x \)-y plane (the centers of the spheres are arranged on a triangular lattice of lattice constant \( a_{\text{eq}} = a/\sqrt{2} \)), but each layer is displaced to the one below by \( d = a(\sqrt{2}/4, \sqrt{6}/12, \sqrt{12}/6) \). In the calculations presented in this paper we have used a spherical wave expansion with a cutoff in the angular momentum of \( l_{\text{max}} = 7 \) and \( p = 37 \) two-dimensional (2D) reciprocal lattice vectors in the \( x-y \) plane-wave expansion. For a nonabsorbing dielectric structure, this choice of parameters provides a fractional rela-
constant spheres are embedded in a low-dielectric constant host medium and are sitting on a triangular lattice of lattice constant infinity in the plane, but to have a finite size along the growth direction. In each plane, the high-dielectric constant spheres are embedded in a low-dielectric constant host medium (here, for simplicity, the dielectric background is assumed to be air) and are sitting on a triangular lattice of lattice constant \( a_{\parallel} = a/\sqrt{2} \). In the numerical simulations, the structure is assumed to extend to infinity in the \( xy \) plane, but to have a finite size along the growth direction.

tive accuracy of \( 10^{-5} \) for the transmittance of an individual layer of spheres [30]. The inverted opal, shown in Fig. 3, is modeled using the same algorithm by interchanging the dielectric constants of the spheres and the embedding medium. In all the simulations, we assume that the photonic crystal sample is sitting atop a very long substrate (100 times thicker than the total height of the photonic crystal) with dielectric constant \( \varepsilon_2 \) and the whole system is placed in air.

A. Transmission spectrum for nonabsorbing inverted opal structure

We begin by evaluating the transmission coefficients for a close-packed inverted opal photonic crystal. For simplicity, we considered here only the case of \( s \)-polarized incident radiation (the electric field of the incident radiation is perpendicular to the plane of incidence). As shown in Fig. 4, for incoming light along the [111] growth direction of a 16 unit cell inverted opal structure, we obtain a very good agreement with the predictions of band structure for an infinite photonic crystal (Fig. 1). The fundamental stop gap (centered around \( \omega = 0.48 \pi c/a \)) and the stop gap between the eighth and the ninth bands (that includes the full photonic band gap of the crystal) correspond to strong dips in the transmission curves. The very small values of the transmission coefficient in these spectral ranges confirm that for a 16 unit cell structure the band gap effect is fully developed. Apparently, the transmission calculations show extra stop bands in the higher-order bands part of the spectral range considered. The low transmission in these spectral regions is not caused by the absence of propagating electromagnetic modes (the band structure clearly shows the existence of propagating modes in these regions) but rather than that by the inability of the incident radiation to couple to the nondegenerate photonic bands along the [111] direction of the fcc lattice. These nonoptically active bands have been thoroughly investigated theoretically [31,32] and have been experimentally observed in 2D photonic crystals [33].

As the angle of incidence is increased (see Figs. 5, 6, and 7), the frequencies that define the stop gap shift and the stop

FIG. 2. (Color online) A close-packed opal structure \( (r/a = \sqrt{2})/4 \) viewed as a sequence of ... ABCABC ... planes grown along the [111] direction. In each plane, the high-dielectric constant spheres are embedded in a low-dielectric constant host medium (here, for simplicity, the dielectric background is assumed to be air) and are sitting on a triangular lattice of lattice constant \( a_{\parallel} = a/\sqrt{2} \).

FIG. 3. (Color online) A close-packed inverted opal structure \( (r/a = \sqrt{2})/4 \) viewed as a sequence of ... ABCABC ... planes grown along the [111] direction. In each plane, the low-dielectric constant spheres (here, for simplicity, we assume air spheres) are embedded in a high-dielectric constant host medium and are sitting on a triangular lattice of lattice constant \( a_{\parallel} = a/\sqrt{2} \).
gaps width decreases. However, if all possible angles of incidence were explored only the stop gaps between the eighth and the ninth bands will survive and their overlap will generate the full band gap shown in Fig. 1.

B. Absorption and thermal power spectra for an inverted opal structure: Photonic crystal as active emitter

We now include the effects of absorption. For simplicity, we assume a close-packed inverted opal of “lossy” air spheres ($\varepsilon_1 = 1 + 0.001i$) in silicon dielectric background ($\varepsilon_2 = 11.9$). The choice of a frequency-independent absorbing medium is made for simplicity. With a frequency independent dielectric constant, it is possible to investigate the effects of absorption throughout the whole spectral range with a single numerical run and to distinguish more easily the effects of the absorption from the effects of the dispersion of the real part of the dielectric constant [34] on the optical response of the photonic crystal sample. Experimentally, the configuration considered here can be realized by infiltrating an absorptive material (such as a gas vapor) in the voids of the inverted opal photonic crystal. The emissivity dependence on normalized frequency and polar angle for both polarizations is presented in Figs. 8, 9, and 10. Several important features are present. The absorption is strongly enhanced at the band edge location for the stop gaps along different propagating directions in the photonic structure. For given directions, the absorption almost reaches unity at the band edge resonance frequencies. This in turn implies that the emission is enhanced up to the pure blackbody limit rate at these frequencies. This observation is consistent with previous one-dimensional calculations [15,16], and recent experimental observations [22]. As noted in the previous work [15,16], around the band edge resonances, the three-

FIG. 5. Transmission spectrum for a 16 unit cell inverted opal structure for $s$-polarized incident light along the [111] direction of the underlying fcc lattice.

FIG. 6. (Color online) Transmission spectra for a 16 unit cell inverted opal structure on a spectral range centered around the low-frequency edge of the first stop gap, for $s$-polarized incident light with increasing angles of incidence with respect to the [111] direction.

FIG. 7. (Color online) Transmission spectra for a 16 unit cell inverted opal structure on a spectral range centered around the full photonic band gap of the underlying lattice, for $s$-polarized incident light with increasing angles of incidence with respect to the [111] direction.

FIG. 8. Absorption spectrum for $s$-polarized incident light on a 16 unit cell inverted opal structure in the case of normal incidence.
dimensional photonic crystal superstrate acts as an antireflective coating, allowing all incident radiations at the frequency to be absorbed—which is the definition of a blackbody. Thus, the emissivity is also enhanced considerably for given spectral ranges and well defined incident directions. This result opens a way to realize a frequency-sensitive and angle-dependent photonic crystal absorber/emitter.

We also obtain that in the presence of the absorption the band edge location shifts and becomes not so well defined. This can be seen in Figs. 9 and 10, where we plot the evolution of the lower edge of the first stop gap and spectral region surrounding the full band gap, respectively, as the angle of incidence departure from the \( \Gamma-L \) direction increases. The absorption spectrum features reflect the spectral dependence of the transmission coefficient for the lossless sample, since for high transmission regions the light travels throughout the photonic crystal sample and has a better chance of being absorbed. This is best illustrated in Fig. 9, where the absorption spectrum features follow closely the transmission spectrum of a lossless photonic crystal from Fig. 6. For a lossless photonic crystal structure, it should be noted that the reflected electromagnetic field carries with it an additional characteristic that is not presented in the reflection spectrum: the penetration depth of the reflected radiation into the photonic crystal sample. The radiation reflected penetrates in the photonic crystal on a range of 2–5 unit cells and the penetration depth is related to the imaginary part of the inverse of the Bloch wave number [35] and is strongly dependent on the incident direction and the frequency of the radiation (the exact angular and spectral dependence are determined by the topology of the photonic crystal along the incident direction considered). Therefore, due to the finite path inside the PC sample part of the radiation that would have been reflected by a large lossless sample is being absorbed. The fraction of the radiation that is absorbed is proportional to the penetration depth, and, implicitly, strongly depends on incident direction and frequency of the radiation. This mechanism is best illustrated in Fig. 10, and determines spectral features in the absorption spectrum that are complementary present in the reflection spectrum and are not visible in the transmission spectrum of a large lossless photonic crystal (see Fig. 7). Consequently, the extra features present in the absorption spectrum may be attributed to the geometrical characteristics of the photonic crystal sample. All the effects of absorption on the optical response of photonic crystals have to be carefully taken into account when designing photonic crystal structures for control of the thermal emission and absorption.

C. Absorption spectrum of an inverted opal structure: Photonic crystal as passive filter

In this section, we consider a finite inverted opal structure consisting of 16 unit cells along the [111] growth direction stacked on a highly absorptive substrate \( (\varepsilon = 11.9 + i) \), which is 100 times thicker than the total height of the photonic crystal, so that it can be considered essentially infinitely thick. The emissivity dependence on normalized frequency and polar angle for \( s \)-polarized incident light is given in Figs. 11 and 12. This configuration models the experimental configuration where a lossless photonic crystal sits on top of a heated hot-plate (substrate). In this case, the photonic crystal acts as a passive filter by blocking the radiation that would normally reach the absorptive substrate and the absorption spectrum of the substrate will in fact probe the transmission spectrum of the photonic crystal coating. In the absence of the photonic crystal coating, the absorptive material interface is highly reflective (if the ambient medium is air, the reflection coefficient at this interface is around 60%). Hence, by itself, the absorptive substrate is not a very efficient absorber, even if its absorption coefficient may have a relatively large value. We note in Figs. 11 and 12 that in the spectral range corresponding to the stop gaps, the absorption is strongly inhibited. However, at the band edge frequencies (which correspond to transmission resonances in the photonic crystal), the absorption is strongly enhanced to almost unity. The photonic crystal behaves as a unidirectional planar blackbody.
system by eliminating the index of refraction contrast presented by the substrate alone. Similar to the one-dimensional case analyzed in Ref. [15], at these select frequencies, all incident radiation tunnels through the photonic crystal into the substrate where it is eventually absorbed, and the total structure acts as a perfect absorber.

Furthermore, we have calculated the frequency-dependent and incident propagation direction-dependent emittance $\mathcal{E}_k(\omega)$, which represents the relative power emitted for a given frequency with respect to a perfect blackbody absorber. To obtain the absolute power spectrum emitted and measured by a distant detector, we need to multiply the emittance (assumed to be equal to the absorbance) by the Planck blackbody power spectrum [see Eq. (2)]. Depending on the temperature, the maximum of a regular blackbody Planck spectrum can be made to coincide with a specific feature of the absorption spectra shown in Fig. 8. In Fig. 13, we plot the normalized power spectra for different directions of propagation in the photonic crystal. We chose to align the lower band edge frequency at normal incidence, $\omega_0=0.73\,\omega_0$ (where $\omega_0=2\pi c/\alpha$), with the maximum of the Planck blackbody spectrum. Using the fact that the Planck’s blackbody spectrum peaks at $\omega_{\text{max}}=2.82\,k_BT/h$, the temperature necessary to obtain this alignment is then determined by

$$k_BT = \frac{0.73}{2.82}h\omega_0.$$  

For an inverted opal with $a=2\,\mu$m, Eq. (5) yields: $T=1873.5\,\text{K}$.

The results presented in Fig. 13, where we show the absolute thermal power spectra for $s$-polarized incident light on a finite inverted opal structure stacked on highly absorptive and very thick substrate for different angles of incidence also suggest an innovative way in realizing frequency and angle-selective thermal absorber/emitter. Since the band edge maxima of the absorption coefficient occur at different frequencies depending on the direction considered, by matching the blackbody emission spectrum peak with a prescribed absorption coefficient along a specific direction, it is possible to achieve an angle-sensitive enhancement of the thermal emission/absorption of radiation. In the present configuration the effect is reduced due to the fact that the band edge falls at relatively high frequency values as compared to the frequency scale in the problem $\omega_0$—the radiative energy density function in Eq. (2) has a maximum at $\omega_{\text{max}}=2.82\,k_BT/h$ of $\langle W(\omega_{\text{max}}, T) \rangle = 1.42 \, k_B^3 T^3/h^2 \pi^2 c^3$, and a full width at half maximum (FWHM) of $\Delta\omega_{\text{BB}}=4.25\,k_BT/h$ between $\omega_1=1.16\,k_BT/h$ and $\omega_2=5.41\,k_BT/h$. By matching the transmission resonance frequency ($\omega_{\text{max}}$) with the peaks of the Planck’s blackbody radiation spectrum, we have $\omega_{\text{max}}=2.82\,k_BT/h$, and then: $\Delta\omega_{\text{BB}}=12.01\,\omega_{\text{max}}$. Thus, the frequency selectivity, $\Delta\omega_{\text{BB}}$ (which, in turn, determines the
angular selectivity) is directly proportional to the band edge frequency. For example, in the configuration considered in Sec. III B, let us align the peak of Planck’s blackbody radiation spectrum to a spectral feature located in the low-frequency part of the spectrum ($\omega \approx 0.12 \omega_0$) and the spectrum is normalized to the blackbody spectrum in free space. The figure illustrates the possibility to achieve angular selectivity for the thermal response of the photonic crystal system and the interplay between the choice of temperature, which determines the maximum of the thermal power at $\omega \approx 0.12 \omega_0$, and the absorption coefficient of the photonic crystal, which give rise to the local maxima located around $\omega \approx 0.45 \omega_0$. The magnitude of the blackbody thermal power spectrum has been scaled down to fit on the same plot.

FIG. 14. (Color online) The absolute thermal power spectra for $s$-polarized incident light on a 16 unit cell inverted opal structure for different angles of incidence at $T=309$ K. The temperature is chosen such that the blackbody peak aligns with a spectral feature located in the low-frequency part of the spectrum ($\omega \approx 0.12 \omega_0$) and the spectrum is normalized to the blackbody spectrum in free space. The figure illustrates the possibility to achieve angular selectivity for the thermal response of the photonic crystal system and the interplay between the choice of temperature, which determines the maximum of the thermal power at $\omega \approx 0.12 \omega_0$, and the absorption coefficient of the photonic crystal, which give rise to the local maxima located around $\omega \approx 0.45 \omega_0$. The magnitude of the blackbody thermal power spectrum has been scaled down to fit on the same plot.

In summary, we have investigated the spectral and directional properties of the emission of thermal radiation of finite inverted opal photonic crystals. The physical origin of the spectral and angular dependence of the thermal emission is determined by the intricate properties of the coupling of the sources of radiation placed inside the photonic crystal and the electromagnetic mode structure inside the photonic crystal.

While a qualitative picture of the thermal emission properties of photonic crystal structures can be inferred from simulations of infinite, nonabsorbing structures (based on local density of states, group velocity, and electromagnetic field modes spatial distribution), the finite character of the dielectric microstructure and the presence of the absorptive material bring with them important changes to this picture. The frequency and angle dependent transmission resonances, the sharpness and the exact position of the band edge frequencies that define the band gap spectral range are strongly dependent on the size of the dielectric microstructure, on the structure topology, and the amount of absorption present. Our analysis shows that in the presence of the absorption into the dielectric microstructure, the transmission coefficient dependence on the frequency presents tails that enter the stop gap (where for a nonabsorbing structure no propagating modes are allowed) and the stop gap range acquires a stronger dependence on the incident propagation direction.

The precise characterization of the angular and spectral dependence of the thermal response of the photonic crystal structure analyzed in this paper can be of direct use in designing highly efficient thermal energy conversion devices. By matching the coefficient of absorption maxima to the blackbody emission spectrum peak, it is possible to achieve a highly angle-sensitive enhancement of the thermal emission/absorption of radiation. The approach that we suggest is to use angle-selective photonic-crystal based absorbers and achieve a reduction of the solid angle over which the absorber emits its energy. An angle-selective absorber has the same functionality as concentrators and could double the efficiency of a thermovoltaic energy conversion device [23].

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THERMAL EMISSION AND ABSORPTION OF...