Monochromatic polarized coherent emitter enhanced by surface plasmons and a cavity resonance

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In this paper we propose and analyze a design of multilayer nanostructure that could be used as a tunable monochromatic polarized thermal emitter in the visible region for any direction with large temporal coherence and spatial coherence extending into the far field. The thermal emitter has a cavity that is surrounded by a thin silver grating having converging-diverging channel on one side and by a one-dimensional (1D) photonic crystal (PhC) on the other side. The large coherence length is achieved by making use of the coherence properties of the surface waves. Due to the nature of surface waves the new multilayer structure can attain the spectral and directional control of thermal radiation with only *p* polarization. Finite element method was used for analyzing the emission properties of the thermal emitter. The resonance condition inside the cavity is extremely sensitive to the wavelength, which would then lead to high emission in a very narrow wavelength band. Such simple 1D multilayer structure should be easy to fabricate and have applications in photonic circuits, thermophotovoltaics and potentially in energy efficient incandescent sources.

I. INTRODUCTION

In a thermal source the light generation at the microscopic level is a spontaneous emission of photon when an emitter thermally excited relaxes to a lower state. Unlike the laser which produces highly directional and monochromatic light, a thermal light source is isotropic with a broad spectrum. But the thermal source of light is coherent in the near field, i.e., within a distance from the surface that is much smaller than the emission peak wavelength of the spectrum.[1–3] The coherence is due to the role of surface waves. A roughness or a grating on the surface can couple these waves to propagating waves, and the coherence properties can be extended into the far field. Thus, by modifying the characteristics of the surface profile the near field properties can be changed to obtain high emission of the surface in a particular direction and at a given wavelength. This has been observed first on a doped silicon grating supporting a surface plasmon polariton (SPP).[4] Similarly, a peak in the thermal emission by gratings on ZnSe,[5] gold,[6] and SiC (Ref. [7]) was also observed. For these grating structures, it was noted that the excited surface waves could couple to the emitted radiation for the *p* polarization only. No lobe of emission has been observed for *s* polarization; since in this case the SPP's or surface waves cannot be present.[8]

An extraordinary transmission through subwavelength holes was observed recently.[9] It was also reported elsewhere that lamellar metallic gratings with subwavelength apertures can have very high transmission resonances.[10] Similarly, a one-dimensional (1D) metallic grating with narrow and deep slits having the shape of a converging-diverging channel (CDC) can exhibit enhanced transmission resonances for wavelengths larger than the periodicity of the grating. The spectral locations of the transmission resonance bands shift close to each other when the gap at the throat of a CDC decreases and have high transmittance in a very narrow energy band.[11] The enhanced transmission through the subwavelength metallic apertures is due to the excited SPP's on the grating surface.

Using the surface waves it was shown that a 1D photonic crystal (PhC) coated with SiC can have coherent thermal emission lobes for both polarizations in the stop band of the PhC.[12] Furthermore, a 1D PhC having metallic films with thickness of the order of skin depth exhibit photonic effects that can be used to engineer the spectral emissivity of the PhC structure.[13] But the emissivity of 1D metallodielectric PhC increases over a broad spectrum and this is not suitable for monochromatic emission applications. A tunable thermal source with narrow angular emission lobe in the near-infrared (NIR) region has been shown using a thin-film structure—based on a vertical cavity and 1D PhC.[14] Yet, this kind of thermal source is not suitable for highly monochromatic applications, because the spectral emission peak has a large full width at half maximum (FWHM). The two-dimensional (2D) periodic metallic structures exhibit optical properties due to the SPP's that can be used as wavelength selective radiation emitters or filters.[15,16] Similarly, it was shown that a 2D PhC made of germanium has coherent thermal emission for a wavelength in the band gap and is due to the leaky surface waves on the air-PhC interface.[17] It has also been shown that the three-dimensional (3D) tungsten PhC can have higher emissivity.[18,19]

There is a lot of scope in achieving various exceptional applications when the unique properties of the PhC's and plasmonics (SPP's) are merged together. In this direction a unique thermal emitter with desired emission properties was realized. Here we could make use of the surface waves that could be present on both the metallic gratings (plasmonics) and in the PhC structure. The results reported in this paper would show significant improvement over the previous work by having emittance with extremely large spatial and temporal coherence. Also the present paper discusses different possible 1D structures for emittance and proposes a final 1D multistructure with emission properties in visible wavelength range similar to laser. Moreover, the present paper would also demonstrate the possibility of tuning the emission to different wavelengths without loosing the sharp emission properties. A physical explanation for the tuning is also pro-
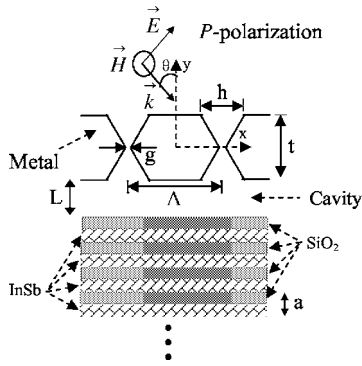
FIG. 1. Schematic view of the thermal emitter geometry with silver (Ag) grating having converging-diverging channel (CDC) with period $\Lambda = 250$ nm, aperture $h = 100$ nm, thickness $t = 100$ nm, and the photonic crystal with unit cell thickness $a = 100$ nm; thickness of SiO$_2$, $d_1 = a/2 = 50$ nm, thickness of InSb, $d_2 = a/2 = 50$ nm along with a cavity filled with air.

vided. Hence, the present 1D multistructure can be used as a good thermal emitter for any wavelength range of interest by changing few parameters and material. In addition the fabrication of the proposed 1D multilayer structure is feasible for scaling up when compared to the fabrication of 2D periodic structures and 3D PhC.

II. EXTRAORDINARY NORMAL EMITTANCE IN NARROW BAND FROM Ag GRATING AND 1D PHOTONIC CRYSTAL

In this paper we propose a design of a potential thermal emitter in the visible range—that is tunable, polarized, highly monochromatic, extremely directional, and with far-field spatial coherence. The proposed thermal source is a multilayer structure with a cavity surrounded by silver (Ag) lamellar gratings having a converging-diverging channel (CDC) on one side and a 1D PhC on the other side. The geometry of the emitter is shown in Fig. 1. The parameters of the CDC gratings are the period Λ, the aperture "h," the depth "t," and the gap at the throat "g." The 1D PhC is made out of alternating layers of SiO$_2$ and InSb, with the layer thickness of each equal to 50 nm. For the present study we used the following grating parameters: $\Lambda = 250$ nm, $h = 100$ nm, and $t = 100$ nm. These grating parameters are used for the entire study and also the cavity is filled with air. In order to arrive at the final design of the potential thermal emitter different possible designs were investigated; namely thin Ag film, thin Ag film with straight channel gratings, thin Ag film with CDC gratings having a different gap at the throat, and a 1D PhC with various cavity lengths.

According to Kirchhoff's law, the spectral directional emissivity $\varepsilon_{\lambda,\theta}$ can be determined by using[20] $1 - \rho_{\lambda,\theta} - \tau_{\lambda,\theta}$ where the spectral-directional reflectance, $\rho_{\lambda,\theta}$ and the spectral-directional transmittance, $\tau_{\lambda,\theta}$ are evaluated by using a plane monochromatic wave incident from the air at an angle of incidence "θ" as shown in Fig. 1. The choice of material on the bottom side of the PhC would not be significant since the wavelength range of interest is in the stop band of the PhC and also the number of unit cells considered for
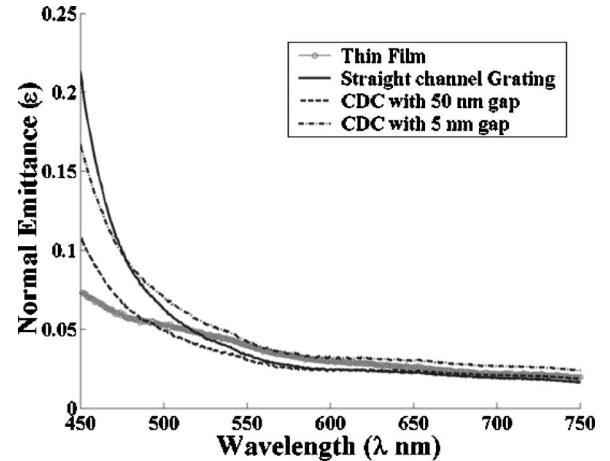

FIG. 2. Normal emittance spectrum with p polarization in vacuum for different thin Ag film structures having the same grating parameters $\Lambda = 250$ nm, $h = 100$ nm, $t = 100$ nm.

the PhC is large. Hence both the reflectance and the transmittance are calculated in air. In the present study both p polarization (magnetic field vector parallel to the gratings) and s polarization (electric field vector parallel to the gratings) were used for the analysis. The electromagnetic fields were assumed to be time harmonic. Therefore the resulting governing equation for the steady-state distribution of the electromagnetic fields is a Helmholtz equation, with the dependent variable ("u") being the magnetic field in the z direction (H_z) or electric field in the z direction (E_z) for p polarization and s polarization, respectively. The dielectric response of the metal (silver) used for grating in this paper is taken from the tables reported in Ref. 21. Commercially available finite element software (FEMLAB 3.1i) was used for solving the governing equation. A 2D computational domain surrounded by either phase-shifted boundary conditions or by a perfectly matching layer (PML) (Ref. 22) was used. The spectral directional reflectance and transmittance of the gratings were calculated from the obtained electromagnetic field distributions. For the wavelength range considered in the paper both SiO$_2$ and InSb are assumed to be lossless dielectrics with refractive indices given by[21] $n_{SiO_2} = 1.46$ and $n_{InSb} = 3.95$. A freely available MIT photonic band (MPB) package was used for calculating the photonic band structure (PBS). The first or lower band gap in the PBS is between the normalized frequencies of 0.136 to 0.217. So, a PhC having a unit cell thickness "a" of 100 nm has a first band-gap wavelength range between 460 nm to 735 nm.

We first investigate the emission spectrum of just a finite thin Ag film with different grating structures in it. Figure 2 shows the p polarized normal emittance for different thin film structures in the PhC stop band wavelength range. The normal emissivity of different structures is low and is monotonically decreasing with the wavelength. Figure 2 also shows that at a smaller wavelength the thin film with the straight channel gratings has higher emissive power than the remaining structures and at a larger wavelength all the structures have the same emissive power. In addition it is seen from Fig. 2 that the thin film slab emittance varies almost linearly with the wavelength, whereas the emittance of dif-
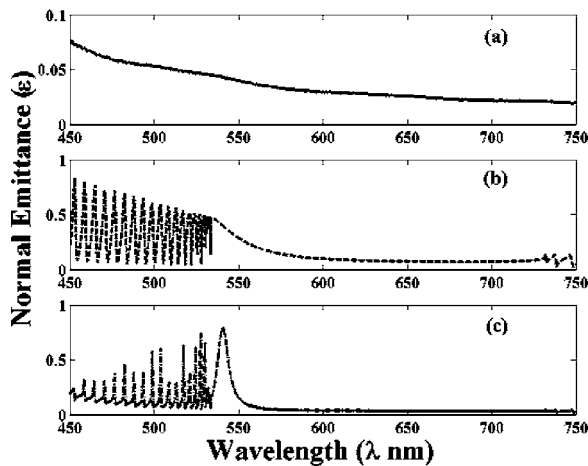
FIG. 3. Normal emittance spectrum with p polarization in vacuum for different thin Ag film structures having the same grating parameters $\Lambda=250$ nm, $h=100$ nm, $t=100$ nm, and a photonic crystal having the parameters $a=100$ nm; $d_1=d_2=50$ nm with no cavity (a) thin film slab, (b) grating with straight channel, and (c) grating with CDC and gap at throat $g=5$ nm.

ferent grating structures changes inversely proportional to the wavelength.

The normal emittance spectrum of various thin film structures and 1D PhC with no cavity is shown in Figs. 3(a)–3(c). Figure 3(a) shows the normal emissivity of the thin film slab on 1D PhC with no cavity, which is similar to the normal emissivity of a thin film slab as shown in Fig. 2. This indicates that the thickness of the slab considered ($t=100$ nm) is larger than the skin depth of the Ag for the wavelength range of interest. The straight channel grating on the 1D PhC with no cavity have multiple emission peaks in the spectrum at lower wavelength range of the spectrum, as can be seen in Fig. 3(b). The presence of these narrow spectral emission peaks is an indication of large temporal coherence of the field at the interface and the coherence time is essentially the lifetime of the collective oscillation.[9] Each of these peaks has a very small full width at half maximum (FWHM) which is required for a good monochromatic emitter. The abrupt changes in the emission spectrum at lower wavelengths with multiple narrow emissive peaks transform gradually to a monotonic decreasing variation at higher wavelengths. At higher wavelengths there are no peaks in the emission spectrum except near the higher band-edge wavelength of 1D PhC where there are a couple of smaller peaks. Also the emissivity is very low at a higher wavelength. The smaller emittance peaks are just outside the wavelength range of the PhC band gap where there are abrupt sharp transmittance peaks. In addition, the small emittance peaks are also due to the sudden dips in the reflectance spectrum of the multistructure. The excitation of surface plasmons (SPs) on the adjacent grating would couple and aid in the transmission of light. The coupling of the SPs would happen only at particular wavelengths. Since the wavelength of transmitted light is outside the PhC band gap then there would be only a small part of the transmitted light from the CDC grating that would be absorbed. Figure 3(c) shows that when there is a CDC grating with 5 nm gap at the throat on 1D PhC with no
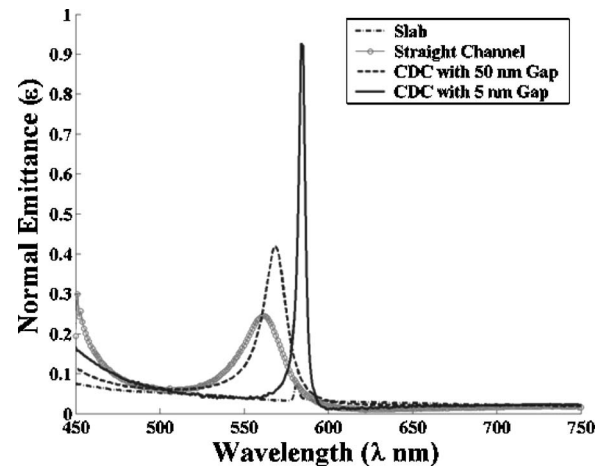

FIG. 4. Normal emittance spectrum with p polarization in vacuum for different thin Ag film structures having the same grating parameters $\Lambda=250$ nm, $h=100$ nm, $t=100$ nm, and a photonic crystal having the parameters $a=100$ nm; $d_1=d_2=50$ nm with cavity length $L=200$ nm.

cavity then some of the narrow emissive peaks at the lower wavelengths will reduce in the magnitude and result in having only a few bigger peaks. The FWHM for the peak at around 540 nm wavelength is about 8 nm. But the presence of a few smaller peaks near the 540 nm wavelength might act like some kind of emissive noise and would make the design not a very good monochromatic thermal emitter. Also the smaller peaks that were present at the higher wavelengths for the straight channel grating case have been canceled out with the smaller gap at the throat of the CDC grating. The multiple peaks appearing in Figs. 3(b) and 3(c) are mainly because of the coupling of SPs on the adjacent gratings which would allow most of the incoming energy or light to get transmitted through the gratings and also due to the strong resonances inside the PhC that would than capture or absorb all the energy resulting in high absorption or emission at different wavelengths. The resonance inside the PhC is all through its length. After a certain wavelength there is no coupling of SPs on adjacent gratings and also there is no resonance inside the PhC.

Figure 4 shows the p polarized normal emittance for various thin film structures and 1D PhC with 200 nm cavity length. This figure shows that the multiple emissive peaks that were present at the lower wavelengths for the various thin film structures and 1D PhC with no cavity would disappear when there is a cavity. It is also shown in Fig. 4 that the thin film slab and 1D PhC with a 200 nm cavity length has a very small peak at around 581 nm wavelength and this peak was not present when there was no cavity [as shown in Fig. 3(a)]. This small emissive peak is not desirable for a good thermal emitter and it becomes bigger when the thin film slab structure is changed to a straight channel grating structure. But the new peak position shifts in spectral location to a lower wavelength of 562 nm and the FWHM of the new peak is around 32 nm. When the film structure changes further to a CDC grating with 50 nm gap at the throat the new peak obtained will have an additional increase in magnitude and the spectral position of the peak shifts to 569 nm wave-
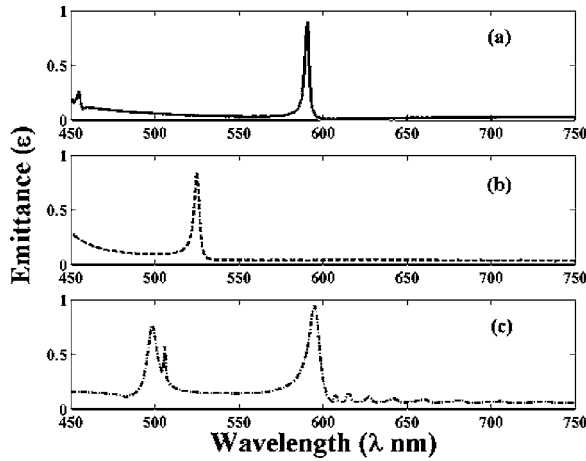
FIG. 5. Spectral emittance in vacuum with p polarization for Ag CDC grating having the parameters $\Lambda = 250$ nm, $h = 100$ nm, $t = 100$ nm, $g = 5$ nm, and a photonic crystal having the parameters $a = 100$ nm; $d_1 = d_2 = 50$ nm with cavity length $L = 500$ nm (a) in normal direction $\theta = 0°$, (b) at $\theta = 34.5°$ from normal, and (c) $\theta = 68.5°$ from normal.

length with FWHM of the peak decrease further to around 17 nm. With an additional decrease in the gap at the throat of the CDC grating to 5 nm the peak formed in the emissive spectrum has a very big increase in the emittance and the spectral location of the emission peak moves to a higher wavelength of around 584 nm. In addition, the FWHM of the new peak decreases even further to around 4 nm, making it an excellent choice for a monochromatic thermal emitter.

The presence of cavity between the CDC gratings and 1D PhC would change the dispersion characteristics of the SPs. The single large sharp emission peak in the case of CDC with 5 nm gap at the throat as shown in Fig. 4 is due to the coupling of the SPs on the adjacent CDC gratings and also due to the cavity resonance. This would then lead to peaks at only particular wavelengths where the cavity resonance such as the harmonic resonances between two walls could happen. Also the presence of narrow emission peak in the spectrum indicates the strong excitation or the resonance of the surface mode. According to the Wiener-Khinchin theorem the width of the spectrum of the field is inversely proportional to the coherence time and similarly a narrow peak in a well-defined direction would produce a large spatial coherence in the field.[23] Hence, the CDC grating with 5 nm gap and 1D PhC with a cavity length of 200 nm can be considered as a monochromatic thermal source with large temporal coherence at 584 nm wavelength.

III. MONOCHROMATIC POLARIZED EMISSION WITH HIGH TEMPORAL AND LARGE SPATIAL COHERENCE

Figures 5(a)–5(c) show the p polarized emittance spectrum of the CDC grating with 5 nm gap at the throat and 1D PhC with 500 nm cavity length for different angles of emission. As can be seen from the figures the emission spectrum is very dependent on the angle of observation—the so-called
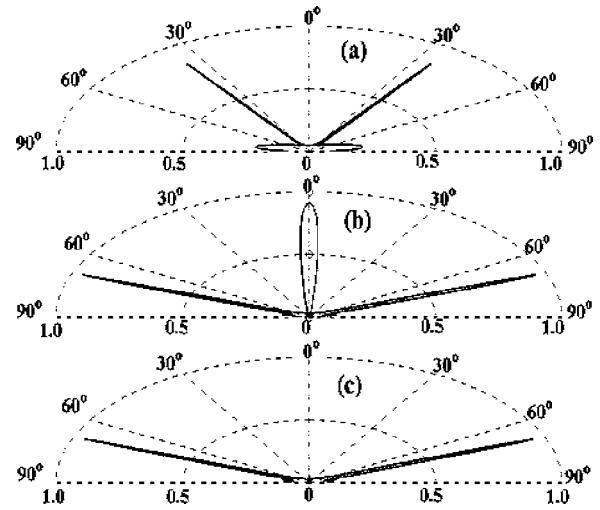

FIG. 6. Directional emittance in vacuum for Ag CDC grating having the parameters $\Lambda = 250$ nm, $h = 100$ nm, $t = 100$ nm, $g = 5$ nm, and a photonic crystal having the parameters $a = 100$ nm; $d_1 = d_2 = 50$ nm with cavity length $L = 500$ nm and with p polarization (a) at wavelength $\lambda = 525$ nm, (c) at wavelength $\lambda = 591$ nm, and (c) at wavelength $\lambda = 595$ nm.

Wolf effect.[24,25] At a normal angle from Fig. 5(a), it can be seen that there is a big emission peak in the spectrum at around 591 nm with a FWHM of about 3 nm. With the angle of emission changed to 34.5° [Fig. 5(b)], the emittance spectrum has changed and the big emission peak has shifted to a lower wavelength of 525 nm with a FWHM of about 4 nm. Figure 5(c) shows the emittance spectrum for the 68.5° angle, with a big emission peak at 595 nm wavelength and a FWHM of about 9 nm. Also there are extremely small peaks in Fig. 5(c) that appear regular and only at wavelengths >600 nm. The transmittance spectrum of only the PhC crystal at 68.5° angle of incidence has regular peaks for wavelengths >600 nm and the spectral locations of the small peaks in the emittance spectrum of Fig. 5(c) are near the PhC transmittance peaks. Hence near the spectral locations where the PhC would have a high transmittance the multistructure would absorb a very small part of the light that is transmitted by the CDC grating. Thus the emission peaks in Figs. 5(a)–5(c) have very high temporal coherence, which is inversely proportional to the width of the spectral emission peak[9] and is decreasing very little with the increase in the angle of emission.

Polarization dependence of the directional emission for the CDC grating with 5 nm gap and 1D PhC with 500 nm cavity length is also investigated. Figures 6(a)–6(c) shows the directional emission for p polarization and for different wavelengths. It is found that for s polarization the directional emission is very low. Figure 6(a) shows the p polarized directional emission at the 525 nm wavelength and the FWHM of the directional peak at 34.5°, is around 1.15° and so, the length of spatial coherence, that is given by[26] $L_{coh} = \lambda / (\pi \Delta \theta \cos \theta)$ is approximately 19.5λ, i.e., around 10.5 μm. The length of the multilayer structure (Le) could be around 2.5 μm (with 10 periods of the gratings). This would then have $L_{coh} \gg Le > \lambda$, making the spatial coherence

length of emission at 525 nm wavelength extend to a far field and at the same time polarization dependent. In addition from Fig. 5(b) it can be noted that the temporal coherence is very high at 525 nm wavelength and 34.5° angle. Therefore the multilayer structure has an almost monochromatic polarization dependent emission with very high temporal coherence and spatial coherence extending into far field. This kind of emission properties make the proposed multilayer structure emit similarly like a laser, but without a stimulated emission and with a thermally excited emission. Figure 6(b) shows the directional emission of p polarization at the 591 nm wavelength. At this wavelength the p polarized directional emission has two peaks in the hemisphere and the peak at the normal angle has a FWHM of around 8° with $L_{coh} \sim 1.4$ μm and this might lead to a local or near-field spatial coherence in normal direction. Whereas, the second peak (at $\theta = 68.5°$) has FWHM of around 2.2° which gives $L_{coh} \sim 14$ μm $\gg$ Le $> \lambda$, and that would make it a far-field coherent emitter at $\theta = 68.5°$. Figure 6(c) shows the p polarized directional emission respectively at the 595 nm wavelength and emission peak is at 68.5° which is almost at the same angular position of the second directional emission peak for the p polarized emission at 591 nm wavelength [Fig. 6(b)]. This is consistent with Fig. 5(c) where the peak of spectral emission is at 595 nm with a FWHM of about 9 nm. The FWHM of the directional emittance peak at 595 nm [Fig. 6(c)] is around 2.1° with $L_{coh} \sim 14$ μm $\gg$ Le $> \lambda$. Therefore from Figs. 5(a) and 6(b), it can be said that the normal emission of the multilayer structure at 591 nm wavelength is very monochromatic with polarization dependence, with large temporal coherence and with small spatial coherence length when compared to the length of the structure. However, Figs. 5(b) and 5(c), Figs. 6(a)–6(c) show that the multilayer structure at some specific angles (at $\theta = 34.5°$ and 68.5°) from normal and at 525 nm and 595 nm wavelengths has emittance similar to a laser; very monochromatic, with high temporal coherence, with polarization dependence, and with spatial coherence length much larger than the wavelength of emission and the length of the structure.

IV. DEPENDENCE OF EMITTANCE PEAK SPECTRAL POSITION WITH CAVITY LENGTH

Normal emittance spectrum with p polarization for the CDC grating with 5 nm gap and 1D PhC with various cavity lengths can be seen in Figs. 7(a) and 7(b). The 100 nm cavity length has one smaller emissive peaks at a lower wavelength. But, when the cavity length is increased to 200 nm then the emissive peak present at a lower wavelength would increase in magnitude and the spectral position of the peak moves to a bigger wavelength or has a redshift. A further increase in cavity length to 300 nm would make the high emissive peak to have an additional redshift. But the spectrum of normal emittance for the 300 nm cavity length has a small peak at the lower wavelength. The FWHM of the emissive peaks for the cavity length of 100 nm and 200 nm are the same and are around 4 nm. For the 300 nm cavity length the FWHM of higher emissive peak is around 5 nm. Hence Fig. 7(a) shows that by varying the cavity length would result in the redshift
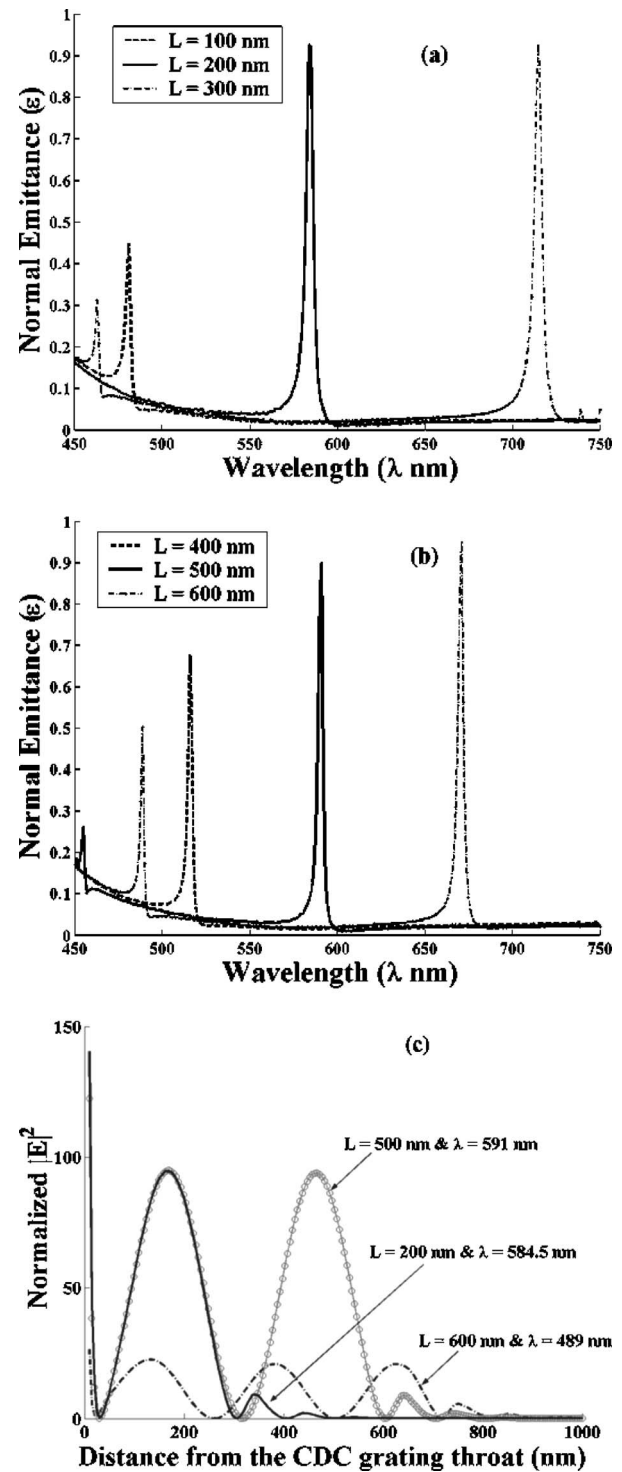

FIG. 7. Normal emittance spectrum with p polarization in vacuum for Ag CDC grating having the parameters $\Lambda = 250$ nm, $h = 100$ nm, $t = 100$ nm, $g = 5$ nm, and a photonic crystal having the parameters $a = 100$ nm; $d_1 = d_2 = 50$ nm (a) with cavity length $L = 100$ nm, $L = 200$ nm, $L = 300$ nm, (b) with cavity length $L = 400$ nm, $L = 500$ nm, $L = 600$ nm, (c) electric field intensity distribution normalized to the incident along the line passing through the center of the CDC grating throat and into the photonic crystal with cavity lengths $L = 200$ nm, $L = 500$ nm, $L = 600$ nm, and at normal emissive peak wavelengths as shown in figure.

of the emissive peak and the FWHM of the peaks will be around 4–5 nm. This would then suggest that the cavity length is a good degree of freedom for achieving a tunable monochromatic thermal emitter for any desired wavelength. The shift in spectral emission is believed to be due to the cavity resonance as shown later. Figure 7(b) shows that an additional increase in the cavity length to 400 nm has the spectral position of the emission peak present at lower wavelengths and the magnitude of the emissivity peak has increased. In addition, at this cavity length there are no emission peaks near the larger wavelengths. When the cavity length is increased further to 500 nm then the emittance peak in the spectrum has further redshifted and is almost in the middle of the wavelength range of interest. But, a closer look on the normal emission spectrum in the lower wavelength range shows that there is a very small peak in the emission indicating that there could be an onset of even higher resonance in the cavity, as shown later. With the cavity length increased to 600 nm the larger emission peak in the spectrum has further redshifted and the smaller emission peak has gained in strength with a similar redshift.

Figure 7(c) shows the electric field intensity distribution normalized to the incident along a line passing through the center of the CDC grating throat and into the 1D PhC. The intensity variation in the cavity seems to be like a first harmonic standing wave between the Ag grating and 1D PhC for a cavity length of 200 nm and at 584.5 nm wavelength. In 1D PhC the electric field intensity decays within a few unit cells. Figure 7(c) also shows the normalized electric field intensity distribution along the line passing through the center of the CDC throat and into the 1D PhC, at the spectral position where the emission spectrum has large emissive peak (591 nm wavelength) for the cavity length of 500 nm. From the figure it can be seen that the 500 nm cavity has a resonance similar to a second harmonic resonance of a standing wave. When the cavity lengths increase beyond a certain range, then there would be an onset of higher order resonances at lower wavelengths and this is also shown in Fig. 7(c). In the figure, the normalized electric field intensity distribution is shown along the same line as the previous cases but for 489 nm wavelength and a cavity length of 600 nm where the spectral emission has a smaller peak at the lower wavelength. The intensity distribution shows that the cavity has a resonance that is similar to a third harmonic standing wave.

The normal emittance spectrum changes with the increase in cavity length because of the cavity resonance that occurs at the emission peak which would occur at different wavelengths depending on the cavity length. The SPs on the grating are affected with the increase in cavity length. At the emittance peak or at the resonance wavelength the surface plasmon near the throat of the grating has a very high electric field magnitude, as is evident from Fig. 7(c). The figure does not show the normalized intensity at the origin due to its very high value. In addition the increase in cavity length would make the magnitude of the electric fields at the throat for the respective resonances to increase. For a particular cavity length and at off resonance wavelengths the electric field magnitude at the throat of CDC is slightly low and there 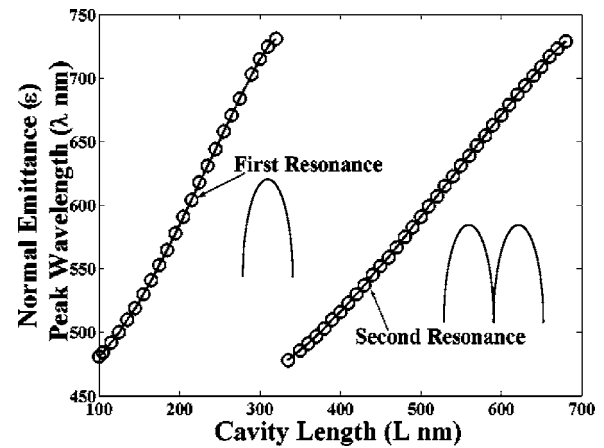is no cavity resonance. Hence the peak in the emittance spectrum is mainly due to the cavity resonance. Hence from Figs. 7(a)–7(c) it is shown that the high absorption or emission is mainly due to the strong resonance in the cavity and the condition for the resonant wavelength changes with the cavity length.

Figure 8 shows the variation of the normal emission peaks with respect to the change in cavity length for different resonances. The first resonance or the first harmonic is due to the half standing wave in the cavity as shown in Fig. 7(c). The second resonance or the second harmonic is due to a complete standing wave in the cavity as shown in Fig. 7(c). The variation in the spectral position of the emission peaks with the change in cavity length seems to be almost linear for both the resonances except at the band-edge wavelengths of the 1D PhC. In addition the first resonance emission peaks needs a smaller cavity length range or a higher slope to span the entire wavelength range of interest when compared to the second resonance emission peaks that needs a larger cavity length range or lower slope for the same wavelength range.

FIG. 8. Variation of the normal emittance peak wavelength with respect to the cavity length for Ag CDC grating having the parameters $\Lambda = 250$ nm, $h = 100$ nm, $t = 100$ nm, $g = 5$ nm, and a photonic crystal having the parameters $a = 100$ nm; $d_1 = d_2 = 50$ nm.

V. CONCLUSIONS

It has been shown that a unique thermal emitter in visible range could be constructed by having a cavity surrounded on one side by a thin CDC Ag grating and a 1D PhC on the other side. The design concept described in the paper can be extended to various wavelength range of interest. The emission properties of the proposed thermal emitter are—highly monochromatic (FWHM ∼4 nm) with large temporal coherence, extremely directional (FWHM ∼1.15°) with far field spatial coherence and is p polarized. The narrow peaks in the spectral and directional emission are mainly due to the strong resonances in the cavity supported by the Ag CDC grating and 1D PhC. The thermal source is tunable to various wavelengths and directions of emission with the choice of right materials along with the parameters of the grating, cavity length, and 1D PhC. Thus, the CDC grating and 1D PhC with a cavity offers a simple multilayer structure that could

have great implications in a variety of applications with diverse wavelength range of interest. Also the present thermal emitter with varying cavity length can be used as a single light source for different colors which could make it an ideal fluorophores for sensitive, multicolor, and multiplexing applications in molecular biology and bioengineering.

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