Active control of narrowband thermal emission with phase-change materials

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Abstract

We propose a framework to design narrowband infrared emitters that can be turned on and off, or emit at arbitrarily different wavelengths, upon the phase transition of a phase change material (PCM). We derive analytically the conditions that must be fulfilled to achieve such spectral functions, suggesting two implementations of this system depending on the nature of the phase transition of the PCM. The system considered is lithography-free, consisting simply of one or several thin emitter layers, a spacer layer including the PCM, and a back mirror. We numerically illustrate on-off spectral switching at a given wavelength with a dielectric-to-dielectric PCM transition (GSST) as well as spectral shifting between two emission wavelengths with a dielectric-to-metal PCM transition (VO$_2$). While idealized materials lead to quasi-perfect behavior, considering real materials leads to parasitic emission, especially with VO$_2$. The model is derived for normal incidence, though we show that the resulting behavior is essentially angle-independent. This work can help design lithography-free diffuse spectrally tunable narrowband infrared sources which are particularly relevant for applications including thermophotovoltaics and thermal camouflage.

I. INTRODUCTION

The ability to control the spectrum, direction and polarization of thermal emission is very valuable for applications including infrared (IR) sources [1, 2], thermal camouflage [3], radiative cooling [4,5] and energy conversion [6]. In particular, the possibility of generating spectrally narrowband IR emission has been the object of a very rich literature [7–14]. While most architectures involve in-plane patterning and/or a large number of layers to reduce the emission bandwidth, surface phonon polaritons (SPhPs) offer naturally narrowband resonances owing to their large quality factors [15]. In particular, it has been shown that few-monolayer SPhP emitters used in a Salisbury screen configuration [16, 17] (a 3-layer structure consisting of an emitter, a dielectric spacer and a mirror, forming a Fabry-Perot cavity whose resonance wavelength matches that of the emitter) can achieve strong narrowband emission [18, 19].

Another prolific area in nanophotonics is the active control of optical properties [20,21], which can take the form of electrical gating [2,13,22–25], optical biasing [26] or applied strain [27]. In the mid-IR region, a popular approach for active tuning is phase-change materials (PCMs), which show a dramatic reversible and (for some of them) non-volatile change in their optical
properties upon heating, leading to a very different spectral response \cite{28–32}. Two classes of materials emerge from this description: those switching from a dielectric to a dielectric phase with different refractive indices, such as some GeSbTe (GST) compounds \cite{33–36}, and those switching from a dielectric to a metallic phase, such as VO$_2$ \cite{37, 38}. They have been studied for various applications including non-volatile optical switching \cite{33, 39–43}, beam switching and bifocal lensing \cite{44}, homeostasis \cite{37}, radiative cooling \cite{38} and thermal camouflage \cite{45, 46}, and are particularly relevant for spectrally-tunable narrowband sources \cite{14, 33, 47–49}. However, simple, lithography-free structures tend to have relatively broadband emissivity \cite{29}. Tunable narrowband sources have been achieved only for more complex structures, with an emissivity which is usually not unitary over the whole range of operation \cite{14, 47, 49}. Furthermore, all these devices have limited spectral tunability as they rely on the temperature dependence of the material’s resonance wavelength.

In this work, we propose a simple framework combining SPhPs and PCMs in a Salisbury screen configuration to design lithography-free narrowband IR emitters with different properties upon phase transition of the PCM. We first derive analytical conditions for unitary and zero emission, leading to simple Fabry-Perot resonance conditions for the spacer. We then apply this versatile framework to 2 configurations. In the first, the emissivity of a single resonance is turned on and off upon phase transition (Fig. 1(a)). In the second, which considers 2 arbitrary emission wavelengths, the emission peak switches from one wavelength to the other (Fig. 1(b)). In both cases, we quantify the performance of optimized devices, considering both idealized and real materials. Finally, we show that the emissivity from these structures shows very little angular dependence, making them great diffuse narrowband thermal sources with spectral tunability.

II. METHODS

We consider a 2-layer stack consisting in an emitter with complex refractive index $n_e$ and thickness $d_e$ on top of a spacer with real refractive index $n_s$ and thickness $d_s$. It is surrounded by 2 semi-infinite media: an upper medium with real refractive index $n_i$ and a back reflector with a complex refractive index $n_b$. The general architecture is illustrated in Fig. 2(a). The emitter layer supports a SPhP resonance at wavelength $\lambda_e$, and its relative permittivity is $\varepsilon_e = n_e^2$. We also define the optical thickness of the spacer as $\Delta_s = n_s d_s$. We restrict our analysis to normal incidence, though it can be extended to any angle (as discussed in section V). Using Kirchhoff’s
law of thermal radiation, we describe emissivity as $\varepsilon = 1 - R$, where $R = |r|^2$ is the reflectivity, $r$ being the Fresnel reflection coefficient of the system. We consider the incident medium to be air ($n_i = 1$) and the back medium to be a perfect reflector ($1/n_b \to 0$). The following results are derived and generalized in Appendix A. Assuming $\Im(\varepsilon_e(\lambda_e)) \gg 1$ (high quality factor for the SPhP), the emitter thickness required to achieve unitary emissivity (resonance) at wavelength $\lambda_e$ is:

$$d_e = \frac{\lambda_e}{2\pi \Im(\varepsilon_e(\lambda_e))},$$  \hspace{1cm} (1)

with a spacer’s optical thickness:

$$\Delta_s^{\varepsilon=1} = \left(m + \frac{1}{2}\right) \frac{\lambda_e}{2}, \quad m \in \mathbb{N}.$$  \hspace{1cm} (2)

On the contrary, the spacer’s optical thickness that leads to zero emissivity is (considering the emitter thickness from Eq. [1]):

$$\Delta_s^{\varepsilon=0} = m \frac{\lambda_e}{2}, \quad m \in \mathbb{N}^*.$$  \hspace{1cm} (3)

Therefore, if $\Im(\varepsilon_e) \gg 1$, $d_e \ll \lambda_e$ and we can neglect the impact of the front layer on the
FIG. 2. (a) Salisbury screen configuration considered for unitary and zero emissivity: a thin emitter is placed on top of a dielectric spacer above a mirror. (b-c) Two ways to modify the optical thickness of the spacer. (b) When the PCM has a dielectric-to-dielectric transition, it can be used as the spacer. (c) When the PCM has a dielectric-to-metal transition, it can be used as a mirror hiding a second spacer which only plays a role in the dielectric phase.

resonance conditions, leading to the resonance and anti-resonance wavelengths of a simple Fabry-Perot cavity (Eqs. 2-3).

The emissivity of such a system can be actively tuned between 0 and 1 by modifying the optical thickness of the spacer, for example using PCMs. A PCM that switches from dielectric to dielectric, with different refractive indices \( n_\alpha \) and \( n_\beta \), can be used directly as the spacer. The index change upon phase transition modulates the optical thickness and thus the emissivity of the system (Fig. 2(b)). A PCM that switches from dielectric to metal can be inserted between two spacer layers such that the thickness of the cavity itself changes upon phase transition (Fig. 2(c)). In its metallic phase, the PCM behaves like a perfect reflector, and the spacer thickness is \( d_\alpha \), while in its dielectric phase, the spacer becomes the combination of the two spacers and the PCM, with a total thickness \( d_\beta \). Note that for the 2-layer model (Fig. 2(a)) to be analytically valid, the PCM should either be extremely thin or have the same refractive index as the spacer when the PCM is in its dielectric phase. The model allows for unitary emissivity at the resonance wavelength to be achieved either in phase \( \alpha \) or \( \beta \) (depending on the thickness of the spacer(s)).

In the following, we illustrate this framework with 2 examples, the first with spectral switching, where emissivity switches from zero to one upon phase transition, the second with spectral shifting, where the emission wavelength is arbitrarily tuned. In both cases, we present the results obtained with both idealized and real materials. The simulations are performed using an in-house transfer matrix method [50].
As a first illustration, we design a system with narrowband unitary emissivity in phase $\alpha$ and zero emissivity in phase $\beta$. The figure of merit of the spectral switch can be defined as the difference in emissivity between both phases at the resonance wavelength of the emitter (equal to 1 in the ideal case):

$$\varphi_{\text{switch}} = \varepsilon^\alpha(\lambda_e) - \varepsilon^\beta(\lambda_e).$$

(4)

From Eqs. 2-3, the system must verify the two conditions:

$$\Delta_s^\alpha = \left( m^\alpha + \frac{1}{2} \right) \frac{\lambda_e}{2}, m^\alpha \in \mathbb{N},$$

(5)

$$\Delta_s^\beta = m^\beta \frac{\lambda_e}{2}, m^\beta \in \mathbb{N}^*,$$

(6)

which imposes

$$\frac{\Delta_s^\alpha}{\Delta_s^\beta} = \frac{2m^\alpha + 1}{2m^\beta}. $$

(7)

Note that the indices $m^\alpha$ and $m^\beta$ should be as small as possible to minimize the spacer thickness.

Here, we consider the configuration where the PCM is used as the spacer (Fig. 2(b)), as it is the simpler configuration. The refractive index ratio should then satisfy Eq. 7, corresponding to:

$$\frac{n_s^\alpha}{n_s^\beta} = \frac{2m^\alpha + 1}{2m^\beta}. $$

(8)

Such a configuration is completely constrained by the refractive indices of the PCM. One very promising material for this application is Ge$_2$Sb$_2$Se$_4$Te$_1$ (GSST) [51], which shows a large refractive index ratio in the IR of about 1.44, close to $3/2$. Therefore, we consider $m^\alpha = m^\beta = 1$, for a system emitting only in its crystalline phase. For illustration, we consider a SiC [52, 53] emitter with a resonance wavelength $\lambda_e = 12.6 \, \mu\text{m}$. Its thickness, determined from Eq. 1, is $d_e = 3.7 \, \text{nm}$.

For the ideal configuration, we consider a dispersionless and absorptionless PCM with refractive indices $n_s^\alpha = 4.60$ and $n_s^\beta = 3.19$ on top of a perfect reflector. The figure of merit is maximized for a spacer thickness $d_s = 2.015 \, \mu\text{m}$, corresponding to an extremely effective spectral switch, with $\varphi_{\text{switch}} = 0.996$ (Fig. 3(a)). The width of the resonance corresponds to that of the SPhP mode in SiC. We note that even with the imperfect index ratio, we can achieve a figure of merit extremely close to one, demonstrating the imperfection tolerance of the approach.
FIG. 3. Spectral emissivity for both PCM phases in the on-off switching configuration, using a 3.7 nm-thick SiC emitter with a dielectric-to-dielectric PCM (a) Considering an idealized 2.015 µm-thick PCM and a perfect reflector. (b) Considering a 2.035 µm-thick GSST spacer and a silver mirror.

For a realistic configuration, we consider the complex refractive indices of Ge$_2$Sb$_2$Se$_4$Te$_1$ [51] and silver [54], with a PCM thickness of $d = 2.035$ µm. The spectral switch remains extremely effective, with $\phi_{\text{switch}} = 0.980$. Nonetheless, we note that emissivity in the crystalline phase is significantly broadened due to parasitic absorption in the PCM and the mirror (3(b)). The origin of this broadening and strategies to mitigate it are discussed in Appendix B.

IV. EXAMPLE 2: SPECTRAL SHIFT BETWEEN TWO RESONANCES

The framework can be extended to several thin emitters stacked on top of each other (or an emitter with several SPhP resonances), as long as there is no spectral overlap between the modes. Here, we design a system with 2 emitters $e_1$ and $e_2$, with unitary emission at wavelength $\lambda_{e_1}$ in phase $\alpha$ and unitary emission at wavelength $\lambda_{e_2}$ in phase $\beta$. We define a figure of merit to quantify the quality of the spectral shift, which tends to one in the ideal case:

$$
\phi_{\text{shift}} = \frac{1}{2} \left[ (\varepsilon^\alpha(\lambda_{e_1}) - \varepsilon^\beta(\lambda_{e_1})) + (\varepsilon^\beta(\lambda_{e_2}) - \varepsilon^\alpha(\lambda_{e_2})) \right]
$$

(9)

We assume the spacer is dispersionless, such that $n_s^{\alpha/\beta}(\lambda_{e_1}) = n_s^{\alpha/\beta}(\lambda_{e_2}) = n_s^{\alpha/\beta}$. The system must satisfy 4 equations:
\[ \Delta \alpha_s = \left( m_1 + \frac{1}{2} \right) \frac{\lambda e_1}{2}, \ m_1 \in \mathbb{N}, \]  
\[ \Delta \alpha_s = m_2 \frac{\lambda e_2}{2}, \ m_2 \in \mathbb{N}^{*}, \]  
\[ \Delta \beta_s = \left( m_3 + \frac{1}{2} \right) \frac{\lambda e_2}{2}, \ m_3 \in \mathbb{N}, \]  
\[ \Delta \beta_s = m_4 \frac{\lambda e_1}{2}, \ m_4 \in \mathbb{N}^{*}, \]  
which imposes a wavelength ratio:

\[ \frac{\lambda e_2}{\lambda e_1} = \frac{2m_1 + 1}{2m_2} = \frac{2m_4}{2m_3 + 1} \]  

(14)

It is impossible to find 4 integers that satisfy Eq. (14) exactly. Nonetheless, one can achieve a spectral shift close to optimal with two fractions close to each other. An important point is that this approach allows arbitrarily large spectral shifts, where conventional spectral shifts are limited to small frequency changes (\(\lambda e_2 - \lambda e_1 \ll \lambda e_1\)).

To illustrate this case, we consider a system where the PCM has a dielectric-to-metal phase transition (Fig. 2(c)). The advantage of this configuration is that any optical thickness ratio can be achieved by adjusting the relative thickness of the spacers, relaxing the number of constrains. We consider two emitters: hBN [55, 56] (\(\lambda e_1 \approx 7.3 \ \mu m\)) and \(\alpha\)-SiC [52, 53] (\(\lambda e_2 \approx 12.6 \ \mu m\)), with thicknesses 3.7 nm and 2.3 nm, respectively (calculated from Eq. 1). The wavelength ratio \(\frac{\lambda e_2}{\lambda e_1} \approx 1.73\) can be well approximated by considering the set of integers \(m_1 = 3, m_2 = 2, m_3 = 3\) and \(m_4 = 6\), leading to \(\Delta \alpha_s \approx 12.7 \ \mu m\) and \(\Delta \beta_s \approx 22.0 \ \mu m\). For the spacer, we consider KBr which is transparent and dispersionless in the spectral region of interest, with \(n_s = 1.52\).

In the ideal case, we consider a perfect mirror and we assume that the PCM switches from a perfect reflector to a dielectric with the same refractive index as the spacer. We obtain an almost perfect spectral shift, with a figure of merit \(\varphi_{\text{shift}} = 0.992\) by considering a first spacer thickness of 8.36 \(\mu m\) and a second spacer + PCM thickness of 6.03 \(\mu m\) (Fig. 4).

For the realistic configuration, we consider Ag [54] as the back mirror, and VO\(_2\) as the PCM [57]. We optimize the thickness of VO\(_2\) as well as that of both spacers to maximize the figure of merit, leading to \(\varphi_{\text{shift}} = 0.840\) with a top spacer thickness of 8.30 \(\mu m\), a bottom spacer thickness of 5.62 \(\mu m\) and a VO\(_2\) thickness of 170 nm. The VO\(_2\) thickness thus obtained roughly corresponds to its skin depth, ensuring a sufficient reflectivity in the metallic phase while minimizing parasitic absorption in the dielectric phase. Still, the far-from-ideal behavior of VO\(_2\) leads
FIG. 4. Spectral shifting between two wavelengths using two SPhP emitters and a PCM with a phase transition from metal to dielectric surrounded by two dielectric spacers. (a) Assuming a perfect dielectric-to-metallic PCM and a perfect reflector (b) With VO$_2$ as the PCM and a silver back mirror.

to significant parasitic emission. In its metallic phase, it is significantly less reflective than noble metals, broadening the emissivity. In its dielectric phase, the imaginary part of the refractive index is not negligible, and increases significantly above 10 µm, leading to parasitic emission. Developing materials with more drastic dielectric-to-metallic transition would enable a behavior closer to the idealized case.

V. ANGULAR DEPENDENCE: DIFFUSE EMITTERS

The model and calculations presented up until this point considered normal incidence. Here, we briefly discuss what happens at non-zero emission angle $\theta$. The effective optical thickness of the spacer depends on the angle, following:

$$\Delta_s(\theta) = d_s \sqrt{n_s^2 - \sin^2(\theta)}.$$  

Therefore, if the refractive index of the spacer is large ($n_s \gtrsim 2$), the optical thickness will only depend weakly on the angle. As a result, the emission should be diffuse (assuming the angular dependence of front reflectivity plays a minor role).

We illustrate this in the context of the realistic spectral switch structure introduced in Fig. 3(b). We show in Fig. 5 the angular and spectral dependence of emissivity for both material phases and both polarizations. In the amorphous phase, the emissivity is close to zero for all angles,
FIG. 5. Emissivity as a function of the emission angle and wavelength in the realistic spectral switch example introduced in Fig. 3(b). (a,b) In the crystalline phase (unitary emissivity), for p and s polarizations, respectively. (c,d) In the amorphous phase (zero emissivity), for p and s polarizations, respectively.

wavelengths and polarizations. In the crystalline phase, the emission is narrowband and diffuse for both polarizations (the second peak peak for high angles in s polarization originates from the parasitic absorption in GSST and Ag). As a result, this lithography-free structure offers a diffuse narrowband IR source which can be turned on and off through control of the PCM phase.
CONCLUSION AND PERSPECTIVES

We have proposed a simple framework to design lithography-free narrowband IR thermal sources which can change their behaviour upon the phase transition of a PCM layer. We suggested different implementations depending on the nature of the phase transition, which we applied to spectral switching (a single emitter with emission turned on and off) and spectral shifting (two emitters, only one emitting in each phase). With ideal, absorptionless materials, it is easy to achieve quasi-perfect behavior even if the conditions are not closely fulfilled. Devices for spectral switching with very high efficiency for all angles should currently be manufacturable, although the relatively thick GSST layers required might be problematic for the phase transition. More complex functions will require further developments in materials to operate at peak efficiency, mostly due to parasitic absorption in the PCM. Additional degrees of control can be considered in order to improve the response and enable new functionalities, for instance by considering dispersive spacers or by adjusting the thickness of the emitters and their position within the stack [50].

The switch configuration is particularly promising for thermophotovoltaic emitters where diffuse narrowband emitters are ideal to achieve high efficiency and power density [58, 59], enabling on-demand energy generation through control of the PCM phase. More generally, these architectures and the associated formalism should be valuable not only for thermal emission applications including infrared sources and thermal camouflage, but more broadly for mid-IR photonic devices such as multi-spectral photodetectors.

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Appendix A: Conditions for unitary and zero emissivity

For normal incidence, the Fresnel reflection coefficient of a 2-layer system takes the expression [60]:

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$$r = \frac{\left[ 1 - \frac{n_i}{n_b} \right] + \left( \frac{n_i n_s - n_e}{n_b n_e} \right) T_e T_s}{\left[ 1 + \frac{n_i}{n_b} \right] - \left( \frac{n_i n_s + n_e}{n_b n_e} \right) T_e T_s} + i \left[ \left( \frac{n_i}{n_e} - \frac{n_e}{n_b} \right) T_e + \left( \frac{n_i}{n_s} - \frac{n_s}{n_b} \right) T_s \right], \tag{A1}$$

with $T_{s/e} = \tan(k_0 n_{s/e} d_{s/e})$, where $k_0 = 2\pi/\lambda$ is the wavevector in vacuum of a monochromatic plane wave with wavelength $\lambda$. If we consider the incident medium is air ($n_i = 1$) and a perfect back reflector ($1/n_b \to 0$), then the reflection coefficient can be written as:

$$r = \frac{n_s - n_e T_e T_s + i \left( \frac{n_s}{n_e} T_e + T_s \right)}{n_s - n_e T_e T_s - i \left( \frac{n_s}{n_e} T_e + T_s \right)}, \tag{A2}$$

with $T_{s/e} = \tan(k_0 n_{s/e} d_{s/e})$, where $k_0 = 2\pi/\lambda$ is the wavevector in vacuum of a monochromatic plane wave with wavelength $\lambda$.

1. Unitary emission

Unitary emission requires $r = 0$, implying that both the real and imaginary part of $r$ should be 0. From Eq. A2, this corresponds to:

$$n_s = T_s \Re(n_e T_e) + n_s \Im\left( \frac{T_e}{n_e} \right), \tag{A3}$$

$$T_s \Im(n_e T_e) = n_s \Re\left( \frac{T_e}{n_e} \right) + T_s. \tag{A4}$$

If there are no further assumptions, this system should be solved directly to determine the optimal thickness of both the emitter and the spacer. Assuming $T_e \approx k_0 n_e d_e$, the system simplifies into:

$$n_s = T_s k_0 d_e \Re(\varepsilon_e) \tag{A5}$$

$$T_s k_0 d_e \Im(\varepsilon_e) = n_s k_0 d_e + T_s. \tag{A6}$$

The condition on the real part (Eq. A5) gives:

$$T_s = \frac{n_s}{k_0 d_e \Re(\varepsilon_e)}, \tag{A7}$$

which we can inject into Eq. A6 to obtain the quadratic equation:
\[ \Re(\varepsilon_e)X^2 - \Im(\varepsilon_e)X + 1 = 0, \quad (A8) \]

where \( X = k_0d_e \). Eq. [A7] admits 2 solutions, of the form:

\[ X = \frac{\Im(\varepsilon_e)}{2\Re(\varepsilon_e)} \left[ 1 \pm \sqrt{1 - \frac{4\Re(\varepsilon_e)}{[\Im(\varepsilon)]^2}} \right]. \quad (A9) \]

Assuming \( \frac{4\Re(\varepsilon_e)}{[\Im(\varepsilon_e)]^2} \ll 1 \), only the solution with the minus sign is compatible with the assumptions. It simplifies to:

\[ X = \frac{1}{\Im(\varepsilon_e)}, \quad (A10) \]

which gives directly Eq. [1] Combining this solution with Eq. [A7] we find:

\[ \Delta_s = \frac{\lambda}{2\pi} \left[ -\arctan \left( \frac{n_s\Im(\varepsilon_e)}{\Re(\varepsilon_e)} \right) + m\pi \right], \quad m \in \mathbb{N}. \quad (A11) \]

In the limit where \( n_s\Im(\varepsilon_e) \gg \Re(\varepsilon_e) \), the arctan term tends to \( \pi/2 \), leading to Eq. [2]

2. Zero emissivity

Emissivity is zero when the reflectivity \( |r|^2 = 1 \). From Eq. [A2] a sufficient condition for unitary reflection is to cancel the term in the parentheses, corresponding to:

\[ \frac{T_s}{n_s} = -\frac{T_e}{n_e}. \quad (A12) \]

Using the linear approximation of \( T_e \) and the emitter thickness obtained for unitary emission (Eq. [1]), we get:

\[ T_s = -\frac{n_s}{\Im(\varepsilon_e)}, \quad (A13) \]

or equivalently

\[ \Delta_s = \frac{\lambda}{2\pi} \left[ -\arctan \left( \frac{n_s}{\Im(\varepsilon_e)} \right) + m\pi \right], \quad m \in \mathbb{N}^*. \quad (A14) \]

Considering \( n_s \ll \Im(\varepsilon_e) \), we get as a first-order approximation:

\[ \Delta_s = \frac{\lambda}{2\pi} \left[ -\frac{n_s}{\Im(\varepsilon_e)} + m\pi \right], \quad m \in \mathbb{N}^*, \quad (A15) \]
and we obtain Eq. 3 in the zeroth-order approximation.

**Appendix B: Reducing resonance broadening**

![Graph](image)

FIG. 6. (a) Spectral emissivity for both PCM phases for the on-off switching of a 3.7 nm-thick SiC emitter illustrated in Fig. 3(b), along with the contribution to emissivity from each layer. (b) The same architecture with a low-index ($n = 1.2$) 1 µm-thick dielectric spacer (and a GSST thickness reduced to 1.53 µm) inserted above the mirror. The contribution from Ag is suppressed, that of GSST is reduced, while the emissivity in the amorphous phase increases slightly.

When considering real materials in the emission switching example, the emissivity is broadened significantly due to parasitic absorption (Fig. 3). Computing the absorption in each layer, we find that about 1/3 of this parasitic emission originates from Ag, and the rest from GaAs (Fig. 6(a)). (Note that the absorption in GSST might be unreliable since the measurement accuracy for the imaginary part of the refractive index $\kappa$ in Ref. [51] is about 0.02, while the data gives $\kappa \approx 0.018$ around 12.6 µm.) We consider adding a low-index dielectric spacer ($n = 1.2$ and thickness 1 µm) below the PCM (with a reduced thickness of 1.53 µm) to decrease emission broadening (Fig. 6(b)). We observe a significant reduction of the mirror’s absorption thanks to a lower electric field intensity at the Ag surface, while GSST absorption is also slightly decreased thanks to the thickness reduction. This means, however, that the optical thickness ratio is no longer optimal, leading to non-zero emissivity in the amorphous phase, and thereby a slight decrease in the figure.
of merit, with $\varphi_{\text{switch}} = 0.939$. 

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