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A Nano-Photonic Filter for Near Infrared Radiative Heater

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Infrared (IR) radiative heating is a highly desirable method for heating as compared to convective heating due to the unprecedented control of radiative energy transfer, leading to a significant increase in energy efficiency. The greatest challenge however with IR radiative heating is its low penetration depth due to the strong IR absorption of the water content in the substance to be heated. Near IR (NIR) heating can circumvent this problem as it has greater penetration depths. The proposed nano-photonic design for NIR filter (or effective selective emitter) has transmissivity of more than 70% in NIR and less than 15% in both visible and IR wavelengths as opposed to currently available IR heaters, which have high emissivity across all wavelengths. This NIR filter can be applied to any radiative heating source to transform it into a NIR radiative heater. We demonstrate this with a simple prototype by applying it in front of tungsten-based incandescent lamp where significant reduction in white glow (glare) was observed. Potential application of this NIR filter would be in heating in both building and industrial sectors where the ability to provide localized heating could lead to significant energy savings. In addition, NIR selective emitters can be applied for power generation by supplying thermophotovoltaics (TPV) with photons at the right wavelengths, which will increase the efficiency of TPV.

1. Introduction

In building sector, U.S. consumes approximately 8% of primary energy each year on space heating; in addition, space heating accounts for approximately 8.7% of domestic greenhouse gas emissions[1]. The current technology for space heating can generally be categorized as centralized heating systems which heat up the entire building or at a minimum a whole room, which is very inefficient due to the transmission loss in air as well as the unnecessary heating of the entire room or building. One strategy that has been investigated in the literature[2] and by ARPA-E (DELTA Program[3]) to reduce the heating demand is to decrease the setpoints inside buildings from 70.5 °F to a lower value. Hoyt et al.[2] calculated the percent annual energy savings that would be achieved by reducing the setpoints from a baseline of 70.5°F and found that reducing the setpoints by 4.5 °F would result in an average energy savings for the entire U.S. of more than[3] 20%. Research performed within the DELTA program[3] of ARPA-E also demonstrated that Localized Thermal Management Systems (LTMSs) could eliminate the discomfort arising from the reduced temperature setpoints by providing spatially resolved localized heating. In another study, Chuah et al. [4] estimated as much 52% reduction in heating energy requirement by using localized heaters.

Commercially available infrared (IR) heaters, have the potential to work as great LTMSs as they can provide directional control of heating and can be very efficient due to the lack of transmission loss in air. However, currently available radiative heaters suffer from two problems as reported in ARPA-E (DELTA program[3]): (1) their strong visible emission, which makes them aesthetically unappealing for building interiors, and (2) the emission peak of commercial IR heaters[3] being at ~2 -3μm, which coincides with strong radiation absorption by water; owing to this IR heaters when placed overhead tend to overheat the exposed areas of the human body (face and head) while under heat the clothed areas (feet and legs), creating discomfort because of the resulting thermal asymmetry.

Similarly in industrial sectors for IR curing of coating materials, IR radiation is not effective due to its small penetration depths into the material, leading to a strong heating effect only at the skin[5]. This results in film formation before full removal of solvents, which affects the film quality and cause surface blisters[5]. Whereas near IR (NIR) curing owing to a larger penetration depth heats up the entire layer volumetrically, resulting in a more homogeneous heating that is more efficient with better film quality. In addition, NIR radiation has also got the advantage of higher energy density resulting in faster curing times[6]. Therefore, NIR radiative heaters have been widely adopted in curing, sintering[7] and food processing[8]. Also, the proposed NIR filter has potential applications in thermophotovoltaics as the bandgaps of most thermophotovoltaic (TPV) materials, including silicon, are in the NIR range[9]. Designing an NIR emitter for a TPV cell will increase the efficiency of TPV cells, which is particularly important for TPVs using fuel (or thermal storage) as a heat source

In order to suppress IR and generate strong NIR radiation, a high heater filament temperature[10] is required to generate thermal radiation that predominately emits in the NIR range. This corresponds to temperatures of roughly 2500K. This high operating temperature causes two major challenges: (1) The system's stability and filament life can be short and unreliable due to the high operating temperature[11], [12] and (2) the strong visible glow of the heater creates a working/living environment that is uncomfortable.

In this work we propose a multilayered photonic structure that filters out the undesired visible and IR radiation from a radiative heater and primarily emit in the desired range of 0.7–2 μm (i.e. in the NIR region). This overcomes the challenges of existing IR heaters and allows the system to operate at lower temperatures leading to longer system life and lower maintenance costs.

2. Fabrication and Characterization of NIR Filter

The proposed photonic NIR filter is composed of an indium tin oxide (ITO) layer on top of a Bragg reflector formed by alternating SiC-SiO_2 layers as shown in schematic in Fig. 1a. The NIR filter structure was deposited via RF magnetron sputtering. The base pressure for the deposition was 10^{-6} Torr. The ITO was deposited with power of 100 W, with partial oxygen pressure of 0.375% and a total Ar & O_2 pressure of 5 mTorr. The substrate heating was used for ITO deposition. The SiC and SiO_2 layers were deposited with power of 150 W, with Ar pressure of 4 mTorr, and 3 mTorr respectively. No substrate heating was applied during the sputtering deposition of SiO_2 and SiC layers. The deposition rate of ITO, SiC and SiO_2 was 12 nm/min, 4 nm/min and 3.2 nm/min respectively.

The NIR filter was characterized using transmission electron microscopy using both parallel beam (TEM) and scanning (STEM) modes. A cross-sectional sample was prepared using focused ion beam (FIB) milling. Fig. 1b and c show the bright field TEM image and elemental map taken using X-ray energy dispersive spectroscopy (XEDS), respectively. Selected area diffraction (SADP) patterns show that the ITO is polycrystalline with mostly columnar grains whereas SiO_2 is amorphous as shown in Fig. 1d. The geometric size (layer thickness and number of layers) of the Bragg reflector was tuned to reflect the visible light at wavelength <0.7 μm, while the ITO layer reflects the infrared radiation beyond 2.5 μm.

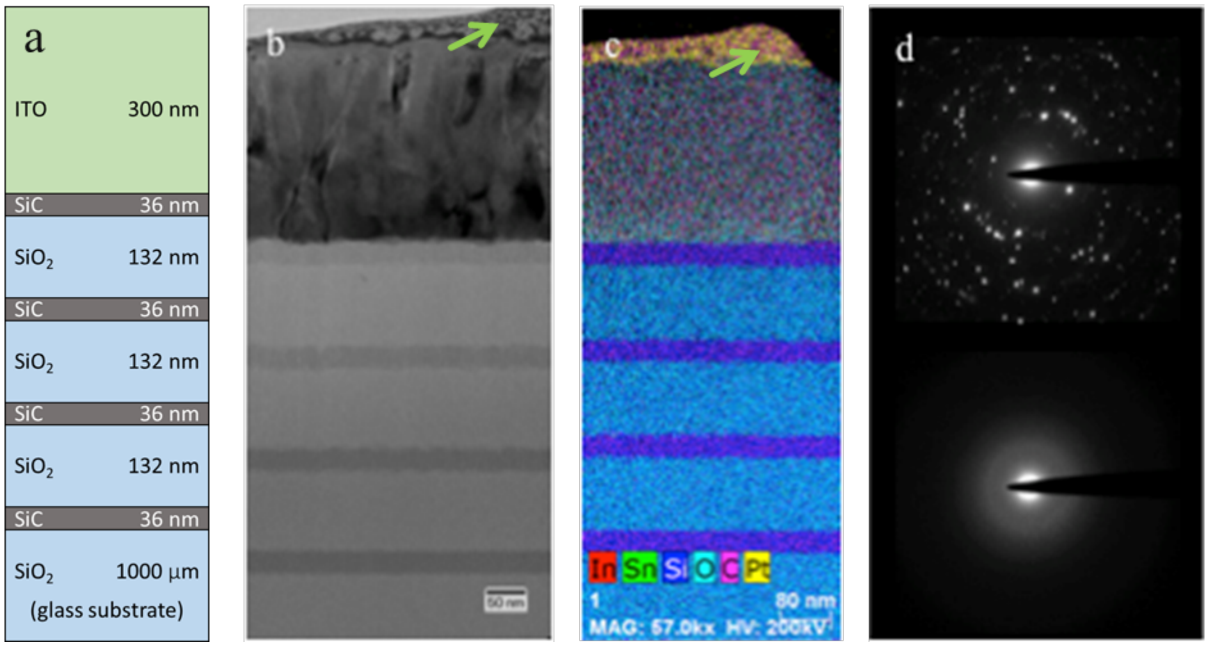

FIG. 1: Structure of NIR photonic filter. a) Schematic and b) bright field TEM image showing of layer arrangements and thickness of the proposed NIR heater; c) XEDS elemental mapping and d) SADP of ITO and SiO_2. The green arrows in (b) and (c) show platinum that was deposited to prepare FIB cross sectional sample of the NIR heater.

3. Spectral Performance of NIR Filter

The multilayer structure was designed using the transfer matrix method[13] to get the desired optical performance. The optical properties of SiC and SiO_2 were obtained from Palik[14], while the optical properties of ITO were obtained using the Drude model [15]:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega / \tau} \tag{1}$$

where ε is the dielectric constant, ω is the angular frequency, τ is the carrier relaxation time, and ω_p is the plasma frequency. The plasma frequency was taken as 1850 THZ and the carrier relaxation time was selected as 6.6 fs from Chen et al. [15] to model the performance of the ITO layer. Although our ITO deposition parameters are not exactly the same as the reference, we used the reference as a good approximation for the design purpose. The modeling is not intended to predict the performance. Since the focus of the current paper is to show a novel application of NIR filter experimentally the transfer matrix model was not repeated after fabrication as the experimental transmissivity of the multi layer structures was better than the model in the NIR region and it overall tracks the model very well over a wide range of wavelength (Fig. 2a). In the future we plan to conduct a systematic study to extract the plasma frequency and the carrier relaxation time of ITO films for our deposition conditions.

The spectral performance of the NIR filter was measured by an FTIR spectrometer. The measured normal incidence transmittance and reflectance for the fabricated NIR filter structure is plotted in Fig. 2, along with the theoretically calculated values [16] using transfer matrix method. The absorbance of the NIR filter was extracted by using the conservation of energy relation: $A = 1 - T - R$, where A, R and T are absorbance, transmittance and reflectance, respectively. The selectivity of the NIR filter can be clearly seen from Fig. 2a where the NIR filter has transmittance of more than 70% in NIR range (i.e., 0.7-2 μm) and less than 15% (average) in most of the visible and IR ranges.

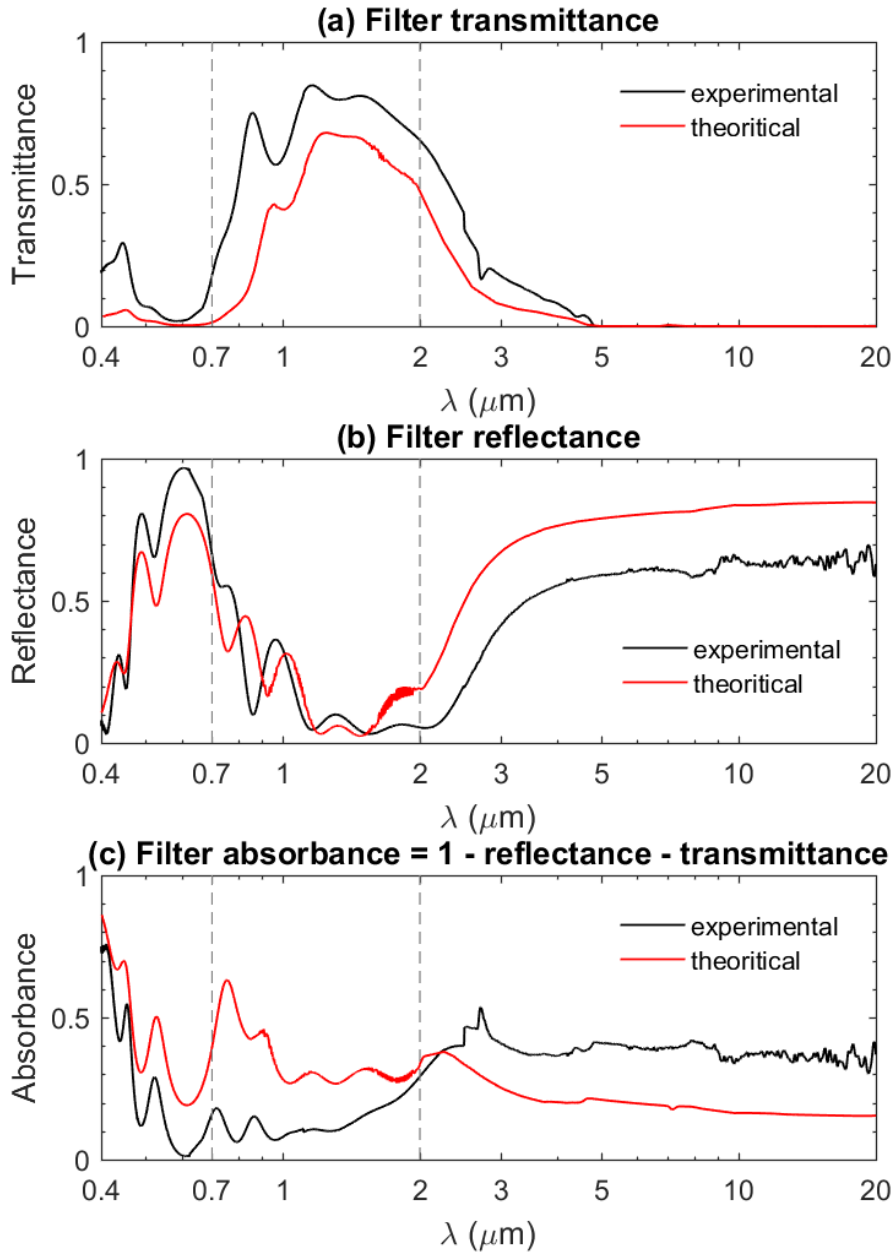

FIG. 2: Measured and theoretical spectral transmittance, reflectance and absorbance for the fabricated NIR filter at normal direction.

The theoretical and measurement results show a reasonable match, especially in the NIR and IR wavelength. The match between theoretical model and experimental data is relatively not as good for absorbance as compared to the transmittance and reflectance because absorbance is a derived quantity by subtracting reflectance and transmittance. As mentioned earlier we have used the theoretical model as design tool than a performance prediction tool. Therefore the models were not recalibrated after the experimental data was obtained. In fact as seen from Fig. 2a the model is predicting worse performance than the actual experimental data, particularly in the NIR region.

The optical properties beyond 2.5 μm are predominately determined by the properties of ITO layer, and a good match between the theoretical model and optical measurement indicates a good approximation of optical properties of ITO. On the other hand, the stop band for transmission in the visible range is narrower for the actual sample compared with theoretical model, which may be because the actual refractive index and thickness for the deposited layers forming the Bragg reflector differ from the theoretical values. The fabricated NIR filter has average transmittance (averaged over relevant wavelengths) of less than 10% in the visible wavelengths and less than 15% in IR wavelengths as opposed to currently available IR heaters where the transmittance is typically constant for all wavelengths. By depositing this photonic structure on the outside of a regular radiative heater/lamp, it will effectively behave as a NIR heater due to the selective NIR transmission of the multilayer coating. Another great advantage of this design is the high temperature stability, since all the materials selected for the design are highly stable at elevated temperatures[17], [18].

A prototype for the NIR radiative heater was assembled by putting the fabricated NIR filter in front of tungsten-based incandescent lamp. To cover the tungsten lamp, three NIR filters of the size 3 inch by 1 inch each were used. Fig. 3 shows photos for incandescent lamps with and without the NIR filters. The suppression of white glow from the NIR filter can be clearly seen by comparing Fig. 3(a) with Fig. 3(b). The leakage of glow is noticeable from the seams between the three NIR filters as pointed out by arrows in the Fig 3b. There is some violet color apparent from this simple prototype. This is because there is a non-negligible transmission in the blue end of visible spectrum as shown in Fig. 2 which could be reduced further in future studies by incorporating rigorous optimization techniques. Note that this NIR filter can be applied to any radiative heating source to transform into a NIR radiative heater. It was very difficult to get spectral performance of the prototype experimentally owing to poor signal to noise ratio i.e., the intensity of the tungsten lamb light is not enough to get accurate spectral measurements. However, we carried out energy analysis to evaluate impact of the filter on the quality of the emitted radiation and energy efficiency as discussed in the section below.

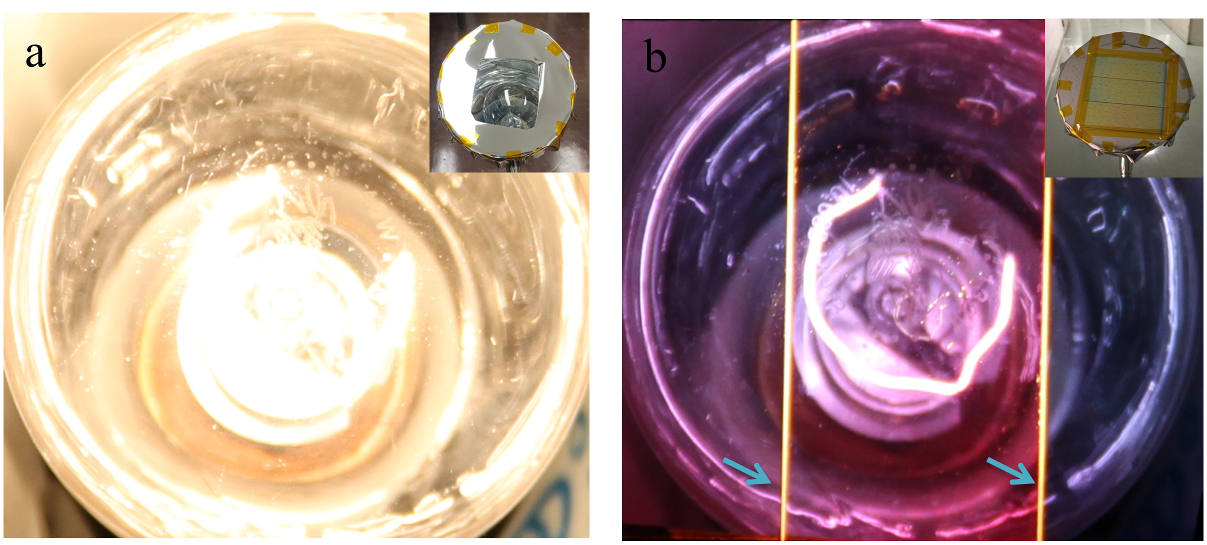

FIG. 3: The filter successfully blocks the visible glare. Photos for the prototype of the NIR heater: a) Incandescent lamp with no NIR filter; b) Incandescent lamp with NIR filter. The arrows point to the seams between the NIR filters where the leakage is visible. Both the photographs were captured under similar conditions: exposure 1/125, ISO 200 and f/5.6.

4. Energy Analysis

In order to calculate the impact of the filter on the quality of emitted radiation and the energy consumption efficiency, we have carried out analysis of a simple representation of the filter-emitter arrangement, an idealized enclosure as shown in Fig. 4a. We used standard ray optics techniques to calculate spectral heat absorbed by the filter and transmitted through the filter, from hot tungsten flat surface. Considering infinite number of reflections between the filter and the emitter, the spectral radiation that is transmitted through (Q_{trans}) and absorbed by (Q_{absorb}) the filter can be calculated from following equations:

$$Q_{trans}(\lambda, \mathrm{T_{emitter}}) = I_{BB}(\lambda, \mathrm{T_{emitter}})\, \epsilon_s \frac{T_r}{1 - R_r R_s}$$

$$Q_{absorb}(\lambda, \mathrm{T_{emitter}}) = I_{BB}(\lambda, \mathrm{T_{emitter}}) \epsilon_s \frac{R_r(1 - R_s)}{1 - R_r R_s}$$

Where R_s is the reflectance of the radiation source (i.e., the tungsten flat surface), which was calculated from tungsten dielectric constant[14] (i.e., reflectance is the absolute value of the square of Fresnel reflectivity). ϵ_s is the emissivity of the tungsten source, which can be calculated from the $\epsilon_s = 1 - R_s$. R_r and T_r are the reflectance and transmittance of the filter, respectively. I_{BB} is the spectral blackbody radiation at a given wavelength and temperature. We calculate the electric energy consumed by the emitter by applying energy conservation law on the enclosure; $Q_{elec} = Q_{trans,total} + Q_{absorb,total}$, where $Q_{trans,total}$ and $Q_{absorb,total}$ are calculated by integrating Q_{trans} and Q_{absorb} over the entire wavelength spectrum.

Using the experimental data of NIR filter as shown in Fig 2, we calculated the portion of thermal radiation in NIR regime that is transmitted through the filter, and compared it with the total radiation transmitted through the filter, for different emitter temperatures (Fig 4b). The analysis shows that around 90% of the radiation emitted is within the NIR range, while the rest of thermal radiation emitted by the emitter is either absorbed by the filter or reflected back to the emitter. The absorption of the filter is not significant in comparison to the total energy transmitted, which is manifested in the high value of total radiation transmitted through the filter compared with electric energy consumed that is displayed in Fig. 4b.

The energy efficiency of our proposed heater based on the enclosure analysis ranges between 0.7- 0.8 as shown in Fig 4b. It has been reported that LTMS with energy efficiencies of 0.35 could achieve 15% reduction in heating energy in buildings annually [3]. Since the energy efficiency for our proposed heater is much higher than 0.35, reduction in heating energy at the building level will be higher than 15%. Therefore in spite of some energy getting trapped due to finite absorptivity of the filter overall at the building level there will be significant energy savings. We would also like to point out that even at temperatures as low as 1500 K, 85% of the transmitted energy is in the NIR range as shown in Fig. 4b. Typically to increase energy emitted in NIR for the conventional NIR heater the filament temperature is increased. This means if the proposed NIR filter is used significant portion of energy can still be in NIR while using much lower filament temperature, which will lead to significantly enhanced reliability/life time of the filament.

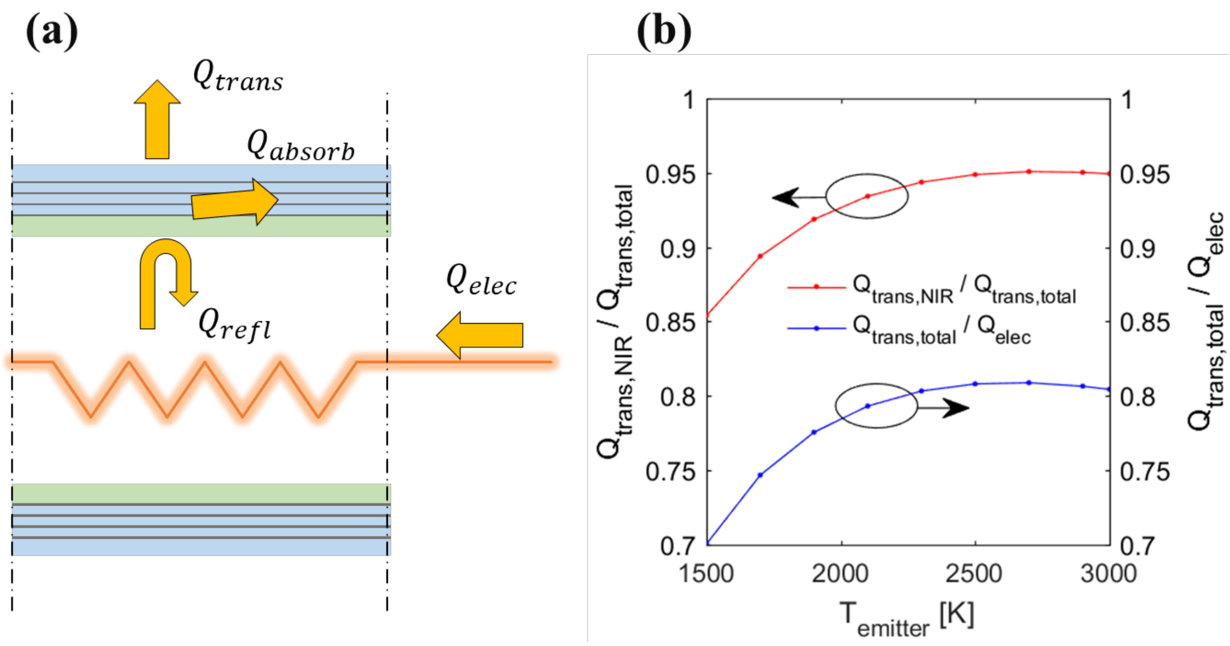

FIG 4: Energy analysis. **a)** Idealized emitter and filter enclosure used to estimate radiative energy transmitted through the filter and absorbed by the filter. b) Portion of transmitted radiation in the NIR regime and the energy efficiency.

5. Conclusions

In summary, we have proposed a photonic multilayer structure as a NIR filter, which can be placed in front of an incandescent lamp to form a NIR radiative heater. The photonic filter selectively transmits the NIR radiation (~90% of the transmitted radiation is in NIR) and suppresses the IR radiation and visible glow that enhances the quality of heating and aesthetics of radiative heaters. The energy penalty to tailor the thermal emission is not significant; the incandescent source and the filter convert over 75% of the electricity input to tailored thermal radiation, which is far above DOE recommended value of 35%.

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Competing interests

The authors declare that they have no competing financial interests

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