Three-dimensional photonic-crystal emitter for thermal photovoltaic power generation

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A three-dimensional tungsten photonic crystal is experimentally realized with a complete photonic band gap at wavelengths $\lambda \leq 3 \ \mu m$. At an effective temperature of $T \sim 1535$ K, the photonic crystal exhibits a sharp emission at $\lambda \sim 1.5 \ \mu m$ and is promising for thermal photovoltaic (TPV) power generation. Based on the spectral radiance, a proper length scaling and a planar TPV model calculation, an optical-to-electric conversion efficiency of $\sim 34\%$ and electrical power of $\sim 14 \ \text{W/cm}^2$ is theoretically possible. © 2003 American Institute of Physics.

There is an emerging interest in using thermal photovoltaic (TPV) cells for electric-power generation. Similar to a solar cell, in which solar radiation is converted into electricity, a TPV cell converts thermal radiation into electricity. The optical-to-electricity conversion is based on photocurrent generation by those photons having energy exceeding the electronic band gap, $E_g$. The portion of photons with $\hbar \omega_{\text{radiation}} < E_g$ is not useful, leading to a lower conversion efficiency. In other words, $E_g$ is the cutoff energy, below which radiation energy is wasted. To maximize conversion efficiency, it is desirable to have a narrow-band spectrum with its radiation energy slightly above the electronic band gap. While the solar spectrum is given, a thermal radiation spectrum may be modified by choice of radiator material, by surface structuring and also by photonic band gap engineering. In particular, a three-dimensional (3D) complete photonic band gap can be used to suppress radiation below the electronic band gap. Meanwhile, emission can be enhanced at a narrow band near a photonic band edge or a narrow allowed band. If both effects are combined, a nearly ideal radiation spectrum can be obtained.

In this letter, a tungsten 3D photonic crystal is experimentally realized with a complete photonic band gap at wavelengths $\lambda \geq 3 \ \mu m$. At a sample temperature of $\sim 1535$ K, the photonic-crystal emission is suppressed in the photonic band gap regime ($\lambda > 3 \ \mu m$), exhibits a peak at $\lambda \sim 1.5 \ \mu m$, and a narrow spectral width of $\Delta \lambda \sim 0.9 \ \mu m$. This nearly ideal radiation spectrum could lead to an optical-to-electric conversion efficiency of $\eta \sim 34\%$ and electric power density of $p \sim 14 \ \text{W/cm}^2$.

The 3D tungsten photonic crystal is fabricated using a modified silicon process. In the first step, a layer of silicon dioxide is deposited, patterned, and etched to create a mold. The mold is then filled with a 500-nm-thick tungsten film and planarized using a chemical mechanical polishing process. The process is repeated several times. At the end of the process, the silicon dioxide is released from the substrate and the sample is a freely standing thin film. A scanning electron micrograph (SEM) image of the fabricated sample is shown in Fig. 1(a). The one-dimensional (1D) rods represent the shortest (110) chain of atoms in a diamond lattice. The rod-to-rodd spacing is $a=1.5 \ \mu m$, the rod width is $w=0.5 \ \mu m$, and rod height $h=0.75 \ \mu m$.

In Fig. 1(b), the computed absorption spectrum for an eight-layer photonic-crystal sample is shown. The absorptance is low for $\lambda > 3 \ \mu m$ (the photonic band gap) and increases slightly at $\lambda \sim 3-4 \ \mu m$ due to a higher tungsten material absorption at these wavelengths. This band gap has been shown to be a complete band gap, capable of trapping light fully in all three dimensions and for both polarizations. Beyond the photonic band gap regime, there are two strong absorptions. One is at $\lambda = 2.5 \ \mu m$ with an absorptance of $\sim 40\%$ and the other at $\lambda = 1.5-1.9 \ \mu m$ with an even stronger absorptance of $\sim 80\%$. The high absorptance is due to a combination of finite tungsten absorption and a high density of

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[Diagram of a SEM view of a 3D tungsten photonic crystal and a computed absorption spectra for an eight-layer 3D tungsten photonic-crystal sample.]
photon-states $D(\omega)$ at a narrow band.\textsuperscript{13–15} As absorption and emission processes have the same physical origin,\textsuperscript{16} a strong narrow absorption is suggestive of a narrow band emission from a photonic-crystal sample.

To achieve emission, the sample is biased by applying a voltage across the photonic-crystal sample and is heated through Joule heating. The emission spectra of the 3D photonic crystal are taken using a standard Fourier-transform infrared spectrometer from a photonic-crystal sample.

In Fig. 2, emission spectra taken at a bias of $V=3$, 4, 5, and 6.5 V are shown, respectively. The effective temperature, averaged over the entire sample, is $T=1190$, 1320, 1440, and 1535 K, respectively. At $T=1535$ K, the emission peaks at $\lambda=1.5$ $\mu$m and has a full width at half maximum of 0.9 $\mu$m. The dashed blue line is a blackbody radiation curve. The electronic band gap wavelength of GaSb is also shown as a red line.

FIG. 2. (Color) The measured photonic-crystal emission power at a bias of $V=3$, 4, 5, and 6.5 V, respectively. The effective temperature, average over the entire sample, is $T=1190$, 1320, 1440, and 1535 K, respectively. At $T=1535$ K, the emission peaks at $\lambda=1.5$ $\mu$m and has a full width at half maximum of 0.9 $\mu$m. The dashed blue line is a blackbody radiation curve. The electronic band gap wavelength of GaSb is also shown as a red line.

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To model photovoltaic energy conversion, a planar system is used to describe radiation heat transfer. This model is intended to evaluate radiator performance and does not include a process to heat the radiator. The radiation model we used is similar to Zenker et al.\textsuperscript{2} As shown in the inset of Fig. 3, the system consists of an emitter, a cell window (model cell front surface), a GaSb photovoltaic cell, and a reflector. Both an ideal and a realistic window reflectivity are considered.\textsuperscript{2} As our photonic-crystal itself emits a spectrally narrow radiation, no filter is used. The GaSb cell is modeled in the context of its thermodynamic limit at $T=300$ K. In this limit, the GaSb internal quantum efficiency is assumed to be 1. For $h\omega_{\text{radiation}}\geq E_g$, it is also assumed that the only loss mechanism in the cell is radiative recombination. The conservation relations between the spectral radiant fluxes are written and symbolically solved using MathCad software. To check our model against Zenker’s, the same cases were run for the thermodynamic limit and for an ideal window reflectivity.

In Table I, the model results are shown for three conventional radiators heated to $T=1500$ K. The BB cavity radiator is a broadband emitter and the Er$_2$O$_3$ and the structured tungsten radiators are selective emitters.\textsuperscript{2} The optical-to-electric efficiency $\eta(\%)$ is defined as: $\eta \text{=} \eta_{\text{el}} Q_{\text{radiation}}$, where $\eta_{\text{el}}$ is the electric power density in W/cm$^2$ and $Q_{\text{radiation}}$ is the total radiation power density. Making allowance for the uncertainties in digitizing the window reflectance in Zenker et al., the agreement for all three emitters is quite reasonable.

Using the same model, the potential performance of a photonic-crystal (PBG) emitter is evaluated. To obtain a more optimal performance, the emission wavelength is scaled by 30%. This scaling corresponds to a photonic crys-
tal with a lattice constant of $a = 1.05 \, \mu m$. In this analysis, a realistic window reflectivity is used. In Fig. 3, the computed efficiency for the PBG emitter and the three conventional emitters is shown. The PBG emitter has a high efficiency of $\eta = 27\% - 33\%$ over the entire temperature range. As the peak PBG-emission wavelength does not shift significantly with temperature (see Fig. 2), this nearly constant efficiency is expected. By contrast, the efficiency of the three conventional emitters exhibits a strong temperature dependence. The efficiency of the blackbody emitter increases from 3% to 15% for $T = 1000–1600$ K. The efficiency is low as only a small fraction of the blackbody radiation satisfies the cutoff condition: $h \omega_{\text{radiation}} \geq E_g$, or $\lambda_{\text{radiation}} \leq \lambda_{\text{band gap}} = 1.73 \, \mu m$. For $T = 1000–1600$ K, a blackbody emission peaks at $\lambda_{\text{peak}} (\mu m) = 2898/(T(K)) = 1.81–2.89 \, \mu m > 1.73 \, \mu m$. Efficiency of the selective emitters, both Er$_2$O$_3$ and structured tungsten, is higher than that of a blackbody emitter. This is due to their shorter peak emission wavelength $\lambda_{\text{peak}} \approx 1.55–1.7 \, \mu m$ and narrower spectral width compared with that of a blackbody emitter.

In Fig. 4, the computed power density is plotted as a function of temperature for the PBG emitter and the three conventional emitters. As temperature is increased, radiation energy density is increased accordingly, leading to higher power density for all four emitters. The highest electric power density is generated by the PBG emitter. At $\langle T \rangle = 1500$ K, the expected electric power is $p = 13$, 2.4, 1.4, and 0.94 W/cm$^2$ for PBG, BB, structured tungsten, and Er$_2$O$_3$ emitters, respectively. This high value of electric power from a PBG emitter is a result of a narrow spectral width and high optical power density as shown in Fig. 2. The structured tungsten and Er$_2$O$_3$ produce the least electric power. This is because, for these selective emitters, their total radiation intensity for $h \omega_{\text{radiation}} \geq E_g$ is less than that of a blackbody emitter. A selective emitter can yield high conversion efficiency, but often at the expense of a lower electric power density.

In summary, a 3D tungsten photonic crystal is realized in the near-infrared wavelengths. Comparing to a blackbody cavity radiation at $T = 1500$ K, its emission has a spectral width nearly 2.5 times narrower and also peaks at a lower wavelength of $\lambda = 1.5 \, \mu m$. Based on the spectral radiance, a proper length scaling and a planar TPV model calculation, a PBG emitter can yield an optical-to-electric conversion efficiency of $\sim 34\%$ and electrical power density of $\sim 14$ W/cm$^2$ at $\langle T \rangle \sim 1535$ K. A PBG emitter, thus, offers a potentially better efficiency and power over conventional emitters, including the blackbody cavity, the Er$_2$O$_3$, and the structured tungsten emitters.

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Black-body radiation is described by Planck’s fundamental law and can be expressed either as an energy flux $dE(\lambda)$ per wavelength interval $d\lambda$ and per solid angle interval $d\Omega$ as a function of wavelength

$$dE(\lambda) = \frac{2\pi^2 c^2}{\lambda^5} \exp\left(-\frac{\pi^2 c^2}{\lambda^5}\right) d\lambda d\Omega,$$

or alternatively as an energy flux $dE(\hbar \omega)$ per photon energy interval $d(\hbar \omega)$ and per solid angle interval as a function of photon energy

$$dE(\hbar \omega) = \frac{(\hbar \omega)^3}{4\pi^2 \hbar^3 c^2} \exp\left(-\frac{\hbar \omega}{kT}\right) d(\hbar \omega) d\Omega.$$

For a laterally extended sample that emits isotropically, Eqs. (1) and (2) must be multiplied by $\pi$ to give the total energy flux emitted into a hemisphere. Lin et al.\(^1\) claim that the energy fluxes emitted thermally by their samples exceed the predictions of Planck’s law [Eqs. (1) and (2)]. It should be emphasized that the measurements in Ref. 1 are related to macroscopic thermal emission into the far field as opposed to “super-Planckian” energy transfer in the near field, which has been discussed in the literature, between two bodies, which are in very close proximity to each other.\(^2\) The thought experiment schematically depicted in Fig. 1 is helpful to assess the claims made in Ref. 1.

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**FIG. 1.** Schematic diagram of an experiment in which a super-radiating photonic crystal and a conventional black body are surrounded by perfectly reflecting walls. Only one of the two bodies, in this case, the photonic crystal, is in thermal contact with the walls of the cavity, which in turn are in contact with a heat reservoir (e.g., the earth). It is further assumed that only the conventional black body obeys the fundamental physical law expressed by Eqs. (1) and (2), whereas the photonic crystal is allowed to emit more radiation, at least in a restricted photon energy interval and into certain directions. A selective filter between the two bodies only transmits radiation from these directions and within the spectral ranges where the photonic crystal is believed to emit more radiation than a black body of the same temperature.
other, a temperature difference thus occurs spontaneously between the two bodies, which could be used to generate electrical energy just by cooling the environment. This is obviously a violation of the second law of thermodynamics, which demonstrates that thermal energy emission into the far field exceeding Planck’s radiation law for black bodies is a thermodynamic impossibility. There is no doubt that the density of states for certain photons (and with it the photon density) can be very large in a photonic crystal. The problem is to get these photons out. Emission of all photons into the smaller number of states in a vacuum would require an increase of the occupation probability, equivalent to reduced entropy. Nature avoids this violation of the second law by totally reflecting those photons, which have no corresponding states in the outside medium.

We were also very surprised to see that the experimental data for $T = 1535$ K shown in Fig. 2 of Ref. 1 exceed the calculated black-body spectrum into a full hemisphere throughout the whole spectral range $6 \mu m < \lambda < 1.3 \mu m$, when both are plotted on the same scale. Even in the spectral range $\lambda > 5 \mu m$ of the photonic band gap, where the absorptance is calculated to be close to zero (Fig. 1 in Ref. 1), the thermal emission exceeds the emission of a black body. The emission by the photonic crystal thus exceeds the prediction of Kirchhoff’s law not only by a factor of 4 to 10, but rather by a factor of 100 to 1000, depending on how close to zero the absorptance really is.

At this point, we wish to emphasize that we have no doubt about the improvements of the absorption/emission properties of the tungsten photonic crystal over conventional tungsten or about the fascinating prospects the impressive photonic crystal structures presented in Ref. 1 may offer to produce e.g. light emitters that are better adapted to the visible spectral range. What we claim here is that the photon flux thermally emitted by a body in a certain direction and in a given photon energy interval, whatever the geometry of that body, cannot exceed the photon flux thermally emitted by a black body of the same temperature, in much the same way as the absorptance of a black body, cannot further be improved to exceed unity. As the thermophotovoltaic (TPV)-efficiency calculations in Ref. 1 are based on the assumption that the photonic crystal emits thermal radiation exceeding the predictions of Planck’s law, the physical significance of these calculations appears to be doubtful.

Nevertheless, we think that the idea of using photonic crystals to produce improved selective emitters for TPV systems is worth further investigation. It must, however, be mentioned that the spectrum at $T = 1535$ K shown in Fig. 2 of Ref. 1 which has a full width half maximum (FWHM) of 0.9 $\mu m$, while certainly better adapted to low band-gap solar cell materials than a pure black-body spectrum, is in fact still a long way from being a “nearly ideal radiation spectrum” for a TPV system as stated in Ref. 1. For instance, the full solar spectrum itself, when modeled as a 6000 K black-body spectrum according to Eq. (1), would have an even narrower FWHM of only $\sim 0.59 \mu m$, which demonstrates that, in the context of selective emitters for TPV systems, the representation of Planck’s law as an energy flux per wavelength interval [Eq. (1)] is somewhat misleading. In the more practical representation of the photon flux per energy interval as a function of photon energy [Eq. (2)], it becomes clearer that this spectrum is indeed very broad, which causes the well known problems with efficient photovoltaic energy conversion and which led to various so-called third-generation approaches, which have been suggested for their solution.

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Response to “Comment on ‘Three-dimensional photonic-crystal emitter for thermal photovoltaic power generation’ ” [Appl. Phys. Lett. 84, 1997 (2004)]

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The goal of our letter is to utilize the experimentally measured photonic-crystal emission spectrum as an input file for predicting the corresponding thermalphotovoltaic (TPV) properties. It is not the intent of this letter to address or claim the physical origin of our photonic-crystal emission, as clearly stated in Ref. 1 p. 381, column 1, last 2–5 lines.

Contrary to what Trupke et al. assumed, the authors did not claim, throughout the letter, that the photonic-crystal emission is thermodynamic in nature. Our sample is, in fact, not a thermodynamic equilibrium system as the sample is neither under an isothermal enclosure nor is it a closed system. Furthermore, electromagnetic wave inside our dispersive (with an imaginary dielectric constant) photonic-crystal structure cannot be defined as a thermodynamic quantity.

Consequently, we have an experimental system in which thermodynamic laws (such as the second law) do not apply. The proposed hypothetical experiment is for a closed wall system, a configuration beyond the claim of our letter.

The authors raise a legitimate concern about the emission of the tungsten photonic crystal exceeding that of the blackbody even in spectral regimes where the calculations presented in Fig. 1 of our work predicts an almost vanishing absorbance by the crystal. Here, we would like to clarify three points. First, the calculations presented in Fig. 1 are performed at room temperature, and record an absorbance of the tungsten crystal of about 3% even in the photonic band-gap region. This mainly arises from the surface layers of the photonic crystal, which experience little photonic band-gap suppression. Second, upon heating the system, one would expect that this surface absorbance would increase considerably, and our measurements do show this occurring, thereby allowing the surface absorbance to increase and, hence, mitigate emission in that regime. Third, we would like to stress that our crystal by no means exceeds the black-body emission in the entire wavelength spectrum, rather the exceeding happens at the neighborhood of the band-edge only. Our publication shows it only occurs in the spectral range from 6 μm to 1.3 μm. Further experimental details about the simultaneous emission enhancement (near the band edge) and suppression (in the band gap) can be found elsewhere.

Trupke’s claim that our emission spectrum is not “an ideal one” as compared to solar radiation is not justified. Solar radiation is generated at a high temperature, T ~ 6000 K. When it arrives on earth, it has a significantly lower peak power of 2000 W/m² μm or 0.2 W/cm² μm (Ref. 5) at λ ~ 450 nm. In contrast, our photonic crystal generates a nearly two hundred times stronger peak power of 40 W/cm² μm at λ ~ 1.5 μm at a manageable temperature of T ~ 1500 K. Thus, our crystal produces far greater power over a narrow band and is the closest there is to “a nearly ideal radiation spectrum” (see Ref. 1 p. 380, column 1, line 21).

It is also to be noted that solar cell and TPV cell are complimentary technologies. A solar cell relies on solar power, but is not effective when it is dark or raining. A TPV cell relies on heating an object at manageable temperatures (T<1800 K) and is not affected by weather conditions.

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Addendum: “Three-Dimensional Photonic-Crystal Emitter For Thermal Photovoltaic Power Generation” [Appl. Phys. Lett. 83, 380 (2003)]

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In our previous paper,1 emission power from an electrically heated photonic-lattice at a given average sample temperature, was compared to that of a blackbody at that same temperature. In this comparison, we measured a lattice emission higher than that of a blackbody. There are questions regarding whether or not this experimental observation is theoretically possible, and if the temperature of the system was sufficiently well known to make this conclusion.2,3 In subsequent experiments, based on those performed in Ref. 1 we have determined that the temperature gradient across the sample was more significant than initially thought. In these subsequent experiments, we see no experimentally significant emission in excess of Planck’s law.

Our modified experimental configuration is shown in Fig. 1. The sample is a six-layer tungsten lattice, having a lattice constant of $a=2.4 \mu m$, a total layer thickness of $\sim 6 \mu m$, and emission peaks at $\lambda \sim 3-4.5 \mu m$. This sample has a larger pitch and emission peaks at longer wavelengths compared to the structures used in Ref. 1. These more robust samples were required for the application of the blackbody paint described below. Performing experiments at longer wavelengths is also expected to enhance the emission process. In Fig. 1(a), a layer of $\sim 100-\mu m$-thick, 3-mm-wide electrically insulating blackbody paint is coated on the center portion of a lattice sample. This is the reference sample for blackbody emission. The uncoated sample is schematically shown in Fig. 1(b). In this experiment the sample configuration was kept the same as in Ref. 1; the only change was in how the temperature was determined. As emission from the coated sample is near blackbody in nature, the temperature may be deduced from its emission peak through Wien’s law. Both the nominally identical coated and uncoated samples are biased the same way and their resistivity change $\Delta R$ recorded. It is assumed that coated and uncoated samples with the same value of $\Delta R$ have the same temperature profile across the sample. This is only an assumption since the total emissivity of the blackbody paint is greater than that of the crystal, and the thermal mass has changed by the addition of the paint. The increase in the total emissivity of the blackbody sample serves to decrease the local temperature; however, the effect of increasing the thermal mass is less clear. For optical measurements, double apertures of 1.5-mm diam. are used to collect close to normal emission from the center portion of the sample, the optical detection configuration was kept the same for both sample types.

The experiment was repeated on three nominally identical samples from the same wafer and representative spectra for the coated and uncoated samples are shown in Figs. 2 and 3, respectively. (The coated sample was also nominally identical to the others prior to the addition of the blackbody paint.) The emission intensity was compared between coated and uncoated samples having the same $\Delta R$ value. Using the approach of Ref. 1 we would have concluded that this sample has a temperature of $\sim 500 K$. However, using Wien’s law to determine the temperature from the blackbody sample showing the same change in resistance we determine a temperature of $\sim 690 K$. From this we conclude that the temperature distribution is nonuniform and that the maximum temperature is significantly greater than that determined previously. For the conditions considered here this temperature difference corresponds to a large variation in thermal emission intensity. To make a more detailed comparison, a plot of the emission intensity of the shortest wavelength emission peak at 3.3 $\mu m$ and the blackbody emission at 3.3 $\mu m$ vs $\Delta R$ is shown in Fig. 4. Again assuming that the same $\Delta R$ leads to the same center temperature, we find that the emission intensity from the lattice is comparable to that from the blackbody. In this comparison we do not have to determine the actual temperature, avoiding potential errors in determining the peak in emission of the blackbody sample.

We do not have sufficient statistics to accurately determine the experimental uncertainty but point out that under these conditions relatively small variations in temperature lead to large changes in emission intensity. We also point out that the errors inherent in this approach tend to suppress emission from the blackbody sample; the blackbody paint is not perfect and the increased total emission intensity from the blackbody sample serves to reduce the center temperature of this sample. We do not believe that the curves in Fig. 4 indicate any experimentally significant deviation from Planck’s law.

FIG. 1. (Color online) (a) a schematic of the experimental setup used for exciting the photonic crystal filament. A current is passed through the crystal by applying a potential across the electrodes. The sample is 8 mm long, 2 mm wide, and 10 $\mu m$ thick. (b) the setup from the black body. The center three millimeters of the sample is coated with and electrically insulating blackbody paint. The blackbody paint is roughly 100 $\mu m$ thick.
In summary, using the approach described here, it is shown that significant deviations in temperature exist. In these subsequent experiments, we observe no experimentally significant deviation from Planck’s law.

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FIG. 2. (Color online) Plots of intensity vs wavelength for the blackbody-paint-coated sample. Different curves were taken at different bias conditions and are therefore at different temperatures. The background has been subtracted out but the intensity has not been corrected for absorption in the optical path.

FIG. 3. (Color online) Plots of intensity vs wavelength for the metallic photonic crystal sample. Different curves were taken at different bias conditions and are therefore at different temperatures. The background has been subtracted out but the intensity has not been corrected for absorption in the optical path.

FIG. 4. (Color online) Plots of intensity (I) vs change in resistance of the 3.3 µm emission peak for three metallic photonic band gap samples (blue) and one blackbody sample (green). We do not believe that there is any experimentally significant emission in excess of Planck’s law evident here.