Photonic Crystals: Shaping the Flow of Thermal Radiation

Ivan Čelanović
Massachusetts Institute of Technology
Cambridge, MA 02139
Overview:

• Thermophotovoltaic (TPV) power generation
• Photonic crystals, design through periodicity
• Tailoring electronic- and photonic bandgap properties: a path towards record efficiencies
• Photovoltaic module: design and characterization
• TPV system design challenges
• Quasi-coherent thermal radiation via photonic crystals
Thermophotovoltaic power generation: basic ideas and concepts
Thermo-photo-voltaic conversion

TPV power conversion describes the direct conversion of thermal radiation into electricity.

Brief History

1956 - Dr. H. Kolm / Dr. P. Aigrain independently propose TPV power conversion concept

1970’s - Loss of interest in TPV due to low efficiencies

1990’s - Advancements in microfabrication technology allow for production of low-bandgap diodes, opening the door for more efficient TPV

1994 - First NREL Conference on TPV Generation of Electricity

2000’s - Photonic crystals for thermal radiation control
Basic TPV energy conversion diagram

1500K blackbody radiation
1300K
1100K
Gallium Antimonide

Heat
Emitter
Blackbody Radiation
Cell Surface Reflection
GaSb
Waste Heat

\[ P_{out} \]
# PV vs. TPV

<table>
<thead>
<tr>
<th>Properties:</th>
<th>PV (Solar Cells)</th>
<th>TPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity Range</td>
<td>Visible and NIR</td>
<td>NIR and IR</td>
</tr>
<tr>
<td>Source</td>
<td>Sun</td>
<td>Thermal emitter</td>
</tr>
<tr>
<td>Source Temperature</td>
<td>Over 5000K (sun’s surface)</td>
<td>1000-1500K</td>
</tr>
<tr>
<td>Distance from Source</td>
<td>Over 90 million miles</td>
<td>µm to cm</td>
</tr>
<tr>
<td>Energy reflected from cell surface</td>
<td>Lost to atmosphere</td>
<td>Recycled to the emitter</td>
</tr>
</tbody>
</table>

Courtesy of DOE/NREL, Credit - Beck Energy.
**TPV Technologies and applications**

**AA radioisotope TPV battery:**
- ~10 mWe
- 30 years life time
- 24% efficiency

Photo courtesy of LLNL.

**micro-TPV power generator (propane/butane operated):**
- 1 Wₑ
- 15% efficiency

10 mm

Courtesy of Klavs Jensen. Used with permission.

**Radioisotope TPV power system for deep space and Mars missions**

Images courtesy of NASA.

Photo courtesy of Sandia National Labs.
Thermophotovoltaics: converting thermal radiation into electricity, with no moving parts

- GaSb (0.72 eV)
- InGaAs (0.6 eV)
- InGaAsSb (0.53 eV)
- Si (1.23 eV)
Photonic Crystals: shaping thermal radiation

![Graph showing the normalized radiated power versus wavelength (µm)]
TPV Technology roadmap: the time is now

**PV diode**
- Si and Ge
- III-V’s (GaSb, InGaAs, GaInAsSb)

**Spectral control**
- Rare earth oxides
- Dielectric stack filters
- Photonic Crystals

**System design**
- JX
- Thermo Power...

Timeline:
- 1950's
- 1960's
- 1970's
- 1980's
- 1990's
- 2000's
Photonic crystals, design through periodicity
Photonic crystals are periodical structures with 1D, 2D or 3D periodicity

1-D Periodicity
\[ \varepsilon(x, y, z) = \varepsilon(x + \lambda_x, y, z) \]

2-D Periodicity
\[ \varepsilon(x, y, z) = \varepsilon(x + \lambda_x, y + \lambda_y, z) \]

3-D Periodicity
\[ \varepsilon(x, y, z) = \varepsilon(x + \lambda_x, y + \lambda_y, z + \lambda_z) \]
Metamaterial:

optical properties determined from its nanostructure
(rather than its composition)

3D photonic crystal: a "semiconductor for photons"

Controlling density of photonic states

\[ u(\omega, T) = N(\omega) \times \left[ \frac{\hbar \omega}{e^{\frac{\hbar \omega}{k_B T}} - 1} \right] \]

controlling thermal emission spectrum

- energy density
- density of photonic modes
- energy in each photonic mode

Free Space

Photonic Crystal

Density of States

Density of States

frequency

wavevector

Photonic Band Gap
Photonic crystals are analogous to semiconductors

- Face center cubic lattice
- Forbiddded bandgap states
- Conduction band
- Electronic bandgap $E_g$
- Valence band
Naturally occurring photonic crystals:

Butterfly wings

Opal

Photo by Megan McCarty at Wikimedia Commons.
Images removed due to copyright restrictions.
Please see: http://www.tils-trr.org/photos/Mitoura-gryMDneo.jpg
http://www.tils-trr.org/photos/Mitoura-gryMVneo.jpg

Fig. 11 in Ghiradella, Helen. "Light and Color on the Wing: Structural Colors in Butterflies and Moths." Applied Optics 30 (1991): 3492-3500.
Fig. S1a, S2, and S4a in Vukusic, Pete, and Ian Hooper. "Directionally Controlled Fluorescence Emission in Butterflies." Science 310 (November 18, 2005): 1151.
Fig. 3 in Pendry, J. B. "Photonic Gap Materials." Current Science 76 (May 25, 1999): 1311-1316.

Tailoring electronic- and photonic bandgap properties: a path towards record efficiencies
Photonic crystal as omnidirectional mirror
1D Si/SiO₂ photonic crystals exhibit omni-directional bandgap.
Spectral characterization of 1D photonic crystal

TEM cross section of LPCVD* grown quarter-wave stack filter with half-layer at the top

Si = lighter layers (170nm)
SiO\textsubscript{2} = darker layers (390nm)

Image removed due to copyright restrictions.
Please see Fig. S2 in Vukusic, Pete, and Ian Hooper. "Directionally Controlled Fluorescence Emission in Butterflies." Science 310 (November 18, 2005): 1151.
Front side PhC designs, 0.72 eV, 0.6 eV, 0.52 eV
1D Si/SiO$_2$ photonic crystals: quarter-wave based stack and genetic algorithm optimized stack as a spectral control tool

Quarter-wave photonic crystal

Genetic algorithm optimized stack

(a) Transmittance vs. Wavelength [µm] for a quarter-wave photonic crystal stack.

(b) Transmittance vs. Wavelength [µm] for a genetic algorithm optimized stack.
Spectral characterization of fabricated 1D photonic crystal

![Graphs showing reflectance vs. wavelength for different TE and TM modes at various angles.](image-url)
Improving the spectral efficiency via selective thermal emission

Selective emitter

Heat

Front-side filter

Waste

Heat
But remember thermal emitter is really hot! (up to 1500K)

Refractory metals have high melting temperature, especially **tungsten**, and that is why it has been used for incandescent light bulbs ever since

*William D. Coolidge*, invented the process for producing the ductile tungsten in 1909 that revolutionized light bulbs and X-ray tubes. His first light bulb was named “Mazda”

Images removed due to copyright restrictions. Please see:

Adding an array of resonant cavities in tungsten can help us tailor the emittance.

Lorentz-Drude model for tungsten

\[ \varepsilon(\omega) = 1 + \sum_j \frac{\omega_{pj}^2}{\omega_j^2 - \omega^2 + i\Gamma_j \omega} \]
2D W PhC as selective thermal emitter:

![Graph showing emittance vs. wavelength for different samples and prototypes.](image1)

- **Prototype 1**
  - Sample area: ~175mm²
  - Period: 1000nm
  - Hole diameter: 910nm
  - Hole depth: 550nm
  - Wall aspect ratio: 0.05

- **Prototype 2**
  - Sample area: ~175mm²
  - Period: 1000nm
  - Hole diameter: 820nm
  - Hole depth: 315nm
  - Wall aspect ratio: 0.09

- **Prototype 3**
  - Sample area: ~225mm²
  - Period: 1000nm
  - Hole diameter: 720nm
  - Hole depth: 600nm
  - Wall aspect ratio: 0.04
2D W PhC exhibits tunable cut-off and resonant enhancement
Fabrication process improvements

• Old

• New
Fabrication Process

Laser Interference Lithography

Development

Soft-mask etch

Hard-mask etch

Photoresist (PR)

ARC

Chrome (Cr)

Tungsten

ARC = Anti-Reflective Coating

Soft-mask removal

Tungsten etch

Hard-mask removal
Tailoring electronic- and photonic bandgap properties: a path towards record efficiencies
GaSb and GaInAsSb diode comparison
Tuning the PhC and PV diode bandgaps: GaSb (0.72 eV) and GaInAsSb (0.52 eV)
Photonic crystals tailoring photonic- and electronic bandgaps

(a) Bandgap tuning

(b) Emittance tailoring
Tuning the PhC and PV diode bandgaps: GaSb (0.72 eV)

<table>
<thead>
<tr>
<th>Spectral efficiency</th>
<th>Above bandgap transmittance</th>
</tr>
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<tbody>
<tr>
<td>1D PhC and 2D W PhC</td>
<td>93 %</td>
</tr>
</tbody>
</table>
Photovoltaic module: design and characterization
Simple TPV diode model

\[ I = I_{ph} - I_0 \left( \exp \left[ \frac{q}{nk_B T_j} (V + IR_s) \right] - 1 \right) - \frac{V + IR_s}{R_{sh}}, \]

(a) Terminal IV curve  
(b) Diode IV curve
GaInAsSb diode characterization cont’d

Packaged Cells

External Quantum Efficiency

EQE (Percent)

V (V)

oc

J (A/cm²)

sc

Wavelength (µm)

E(1000)

0 10 20 30 40 50 60 70 80 90 100

1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6

0 10 20 30 40 50 60 70 80 90 100

1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6

-2 -1 0
GaInAsSb diode characterization

![Diode images](image1)

![Graphs](graph1)
MIT µ-TPV Generator Project
Key innovations in: photonic crystals, MEMs reactors, power electronics, PV
Photonic crystals tailoring photonic- and electronic bandgaps

(a) Bandgap tuning

(b) Emittance tailoring
Robust, integrated catalytic micro-reactor design
Integrated power electronics controller

Cell I-V Characteristic

MPPT Startup Sweep

MPPT Steady State

single chip integrated MPPT
Quasi-coherent thermal emission via photonic crystals

• Vertical-cavity resonant thermal emitter
• 2D PhC slab resonant thermal emission
**Broad-band spectral control**

![Broad-band spectral control graph](image1)

**Narrow-band spectral control**

![Narrow-band spectral control graph](image2)
Vertical cavity resonant thermal emitter is highly-directional, quasi-coherent radiation source
Vertical cavity resonant thermal emitter: narrow-band, highly directional and...
Quasi-coherent thermal emission via photonic crystals

- Vertical-cavity resonant thermal emitter
- 2D PhC slab resonant thermal emission
Black/Gray-Body Physics

Ref: Max Planck, Annalen der Physik, 4, 553, (1901).
Modes of a 2D PhC slab
Fano resonances of a 2D PhC slab

Thermal emittance of a 2D PhC slab

Im(ε) ≈ 0.005

Dependence on angle of observation
Analytical understanding of Fano resonances

\[ |a_{PhC}|^2 = \frac{2}{Q_{ABS} Q_{RAD}} \left( \frac{\omega}{\omega_{FANO}} - 1 \right)^2 + \frac{1}{Q_{RAD}} \left( \frac{1}{Q_{RAD}} + \frac{1}{Q_{ABS}} \right)^2 \]

\[ Q_{ABS} = \frac{\varepsilon_R}{\sigma \varepsilon_I} \]

\[ Q_{ABS} = Q_{RAD} \Rightarrow |a_{PhC}|_{MAX} = 50\% \]
Rules for designing thermal emission

$\omega_{\text{EMIT}}(\theta)$:
- slab thickness
- $\text{Re}(\varepsilon)$
- lattice constant

$\Gamma_{\text{EMIT}} \Leftrightarrow Q_{\text{RAD}}$:
- “size” of holes

Peak emission $\Leftrightarrow Q_{\text{ABS}}$:
- $\text{Im}(\varepsilon)$

\[ |a_{\text{PhC}}|^2 = \frac{2}{Q_{\text{ABS}} Q_{\text{RAD}}} \left( \frac{\omega}{\omega_{\text{FANO}}} - 1 \right)^2 + \left( \frac{1}{Q_{\text{RAD}}} + \frac{1}{Q_{\text{ABS}}} \right)^2 \]
An example of thermal design

No absorption, $k_x = 0.2$ ($2\pi/a$)

- $Q_{RAD}=370$
- $Q_{RAD}=2000$

Frequency (c/a)

Loss in Si ($\lambda=5\mu m$)

Thermal Emission [a.u.]

- $T = 750K$
- $T = 1000K$
Quasi-coherent thermal radiation: summary and opportunities

• PhC’s offer unprecedented opportunities for tailoring thermal emission spectra

• Highly anomalous thermal spectra can be obtained

• Even dynamical tuning of spectra is possible

• Research in the combined near-field and quasi-coherent PhC radiation is opening up new frontiers

• Possible applications include: masking thermal targets, coherent thermal sources, high-efficiency TPV generation, chemical sensing, etc.
2.997 Direct Solar/Thermal to Electrical Energy Conversion Technologies
Fall 2009

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