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Analysis of TPV Network Losses (a Presentation)

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Analysis of TPV Network Losses

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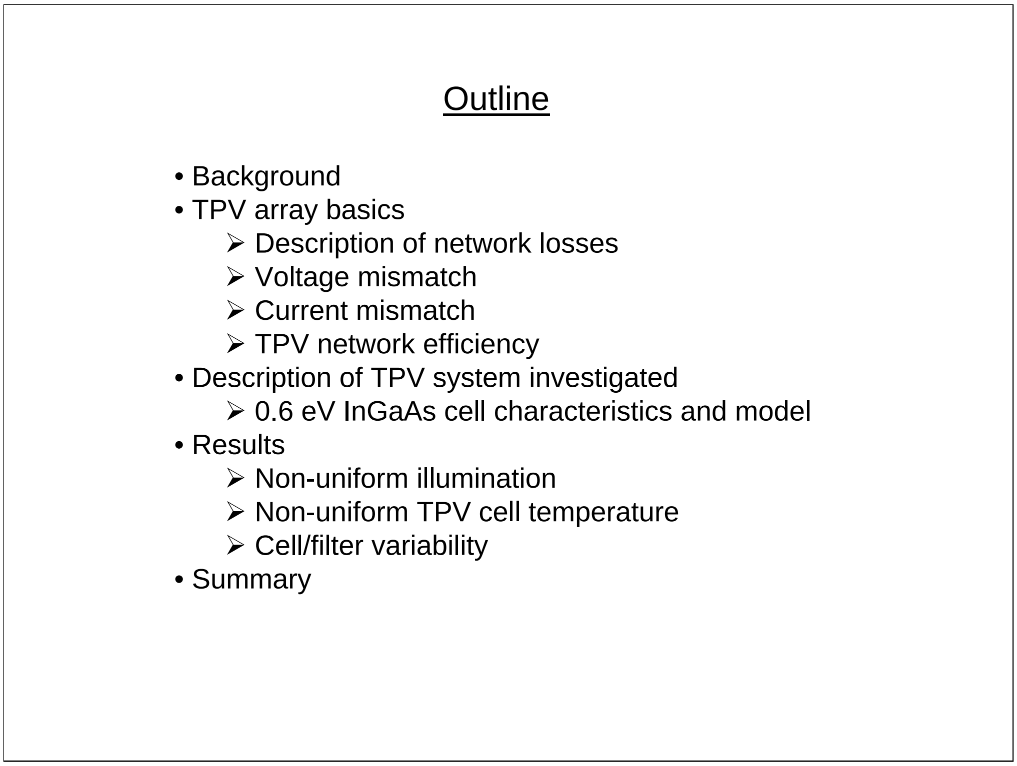
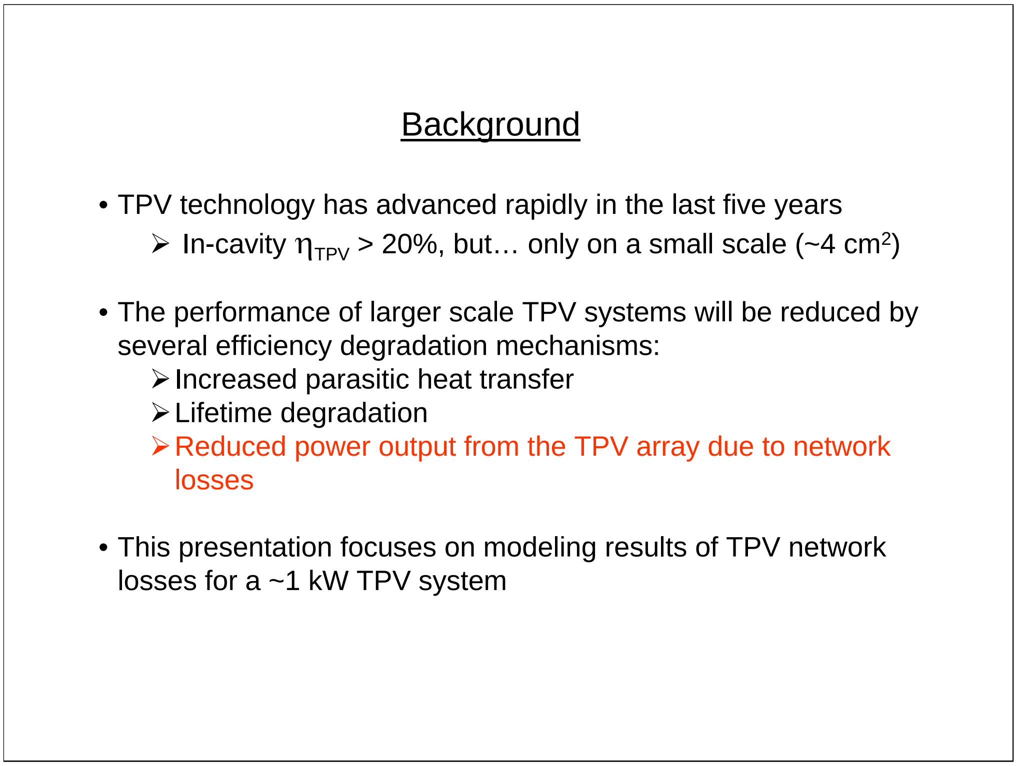
This talk focuses on the theoretical analysis of electrical losses associated with electrically networking large numbers of TPV cells to produce high power TPV power generators.



Outline

- Background
- TPV array basics
    - Description of network losses
    - Voltage mismatch
    - Current mismatch
    - TPV network efficiency
- Description of TPV system investigated
    - 0.6 eV InGaAs cell characteristics and model
- Results
    - Non-uniform illumination
    - Non-uniform TPV cell temperature
    - Cell/filter variability
- Summary

The outline of the presentation is described above.

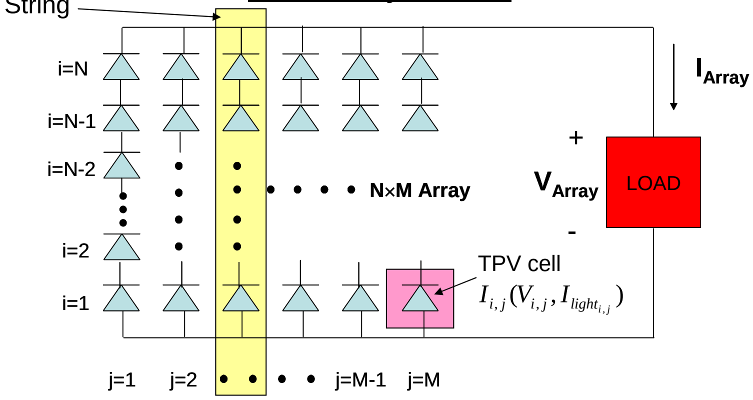


Background

- TPV technology has advanced rapidly in the last five years
  - ➢ In-cavity η_{TPV} > 20%, but… only on a small scale (~4 cm^2)
- The performance of larger scale TPV systems will be reduced by several efficiency degradation mechanisms:
  - ➢ Increased parasitic heat transfer
  - ➢ Lifetime degradation
  - ➢ Reduced power output from the TPV array due to network losses
- This presentation focuses on modeling results of TPV network losses for a ~1 kW TPV system

High efficiency technology demonstrations have been achieved on a small scale (4cm^2 / approximately 2 Watts), however we anticipate some efficiency degradations when scaling up to large power TPV systems (for example conduction heat transfer through structural elements, parasitic radiative heat transfer to inactive regions of the optical cavity, end of life performance degradation, and electrical networking losses). This talk addresses predictions of electrical networking losses for a 1kW TPV system.

TPV Array Basics



- N = number of TPV cells connected in series to form a string
- M = number of strings connected in parallel to form the array
- $I_{string,j} = I_{i,j}$ → cells within a string operate at the same current
- $V_{string,j} = \sum_{i=1}^{N} V_{i,j}$ → string voltage = sum of voltages of cells within string
- $V_{Array} = V_{string,j}$ → strings within the array operate at the same voltage
- $I_{Array} = \sum_{j=1}^{M} I_{string,j}$ → array current = sum of currents of strings

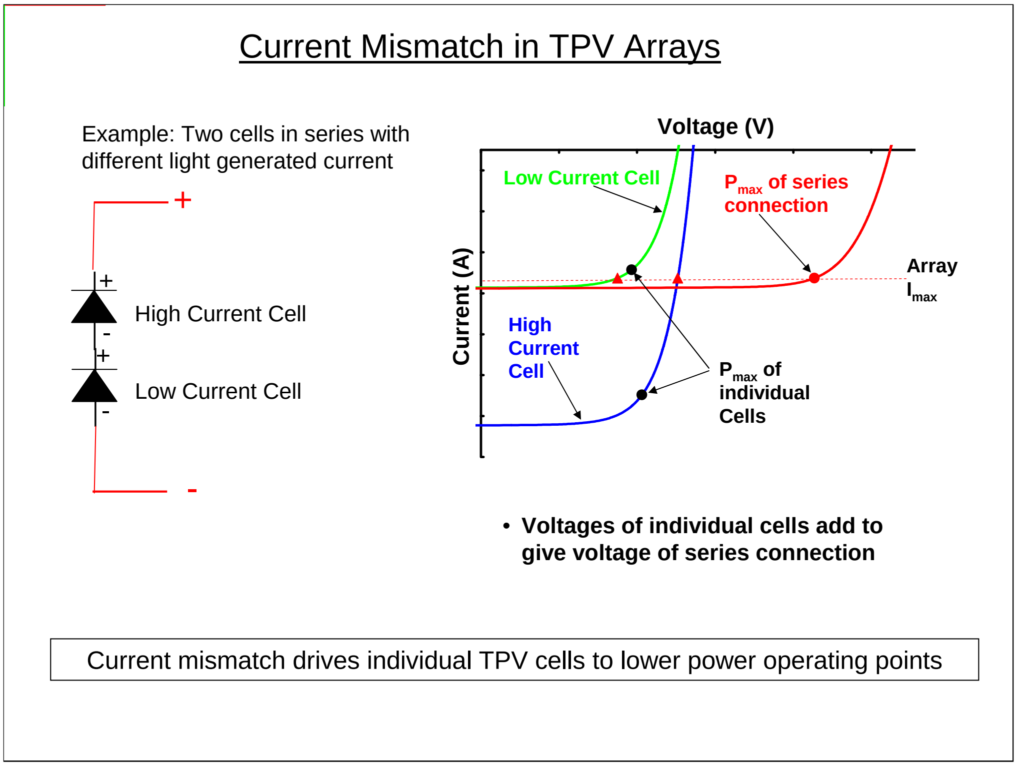
This slide provides a very general overview of the electrical networking problem. TPV diodes/cells are arranged in series/parallel interconnections to provide power (current x voltage) to a load. Basic circuit analysis (Kirchoff's Law) dictates continuity of current flow within series connected strings and equivalent voltages across parallel connected circuits. These boundary conditions will dictate the operating points of individual TPV cells for given system load condition. If the individual TPV cells are mismatched for any reason (e.g. variability of diode characteristics, differing illumination levels per cell, differing cell operating (cold side) temperatures), the mismatched impedances will cause some degree of internal power dissipation within the cells in the network. In other words the array's maximum output power will always be less than or equal to the sum of available photovoltaic power from the individual cells, where the equal applies only to perfectly uniform conditions.

Description of Network Losses

- Power dissipated within the TPV network
- Potential causes of network losses
    1. Current/Voltage mismatch
        - Non-uniform illumination
            - Radiator temperature gradients
            - Cavity photonics
        - Non-uniform TPV cell temperature
        - Cell/filter variability
    2. Others (not considered in this study)
        - Interconnects (negligible)
        - Protective Devices
            - Blocking/bypass diodes

This slide gives a summary list of the origins of networking losses in arrays of photovoltaic devices. The first list states the issues expected from non-ideal optical cavities, radiator temperature profiles, cold side temperature gradients, and diode/filter manufacturing variability. The effect of metal interconnects is found to be negligible compared to the internal resistance of the TPV cells here.

Protective devices are often implemented to protect against faults (short to grounds) and large networking losses; these protective devices themselves require a small amount of the network power to operate, thus their presence will reduce networking efficiency by a small amount. These fault protection devices are not considered in this analysis.



Current Mismatch in TPV Arrays

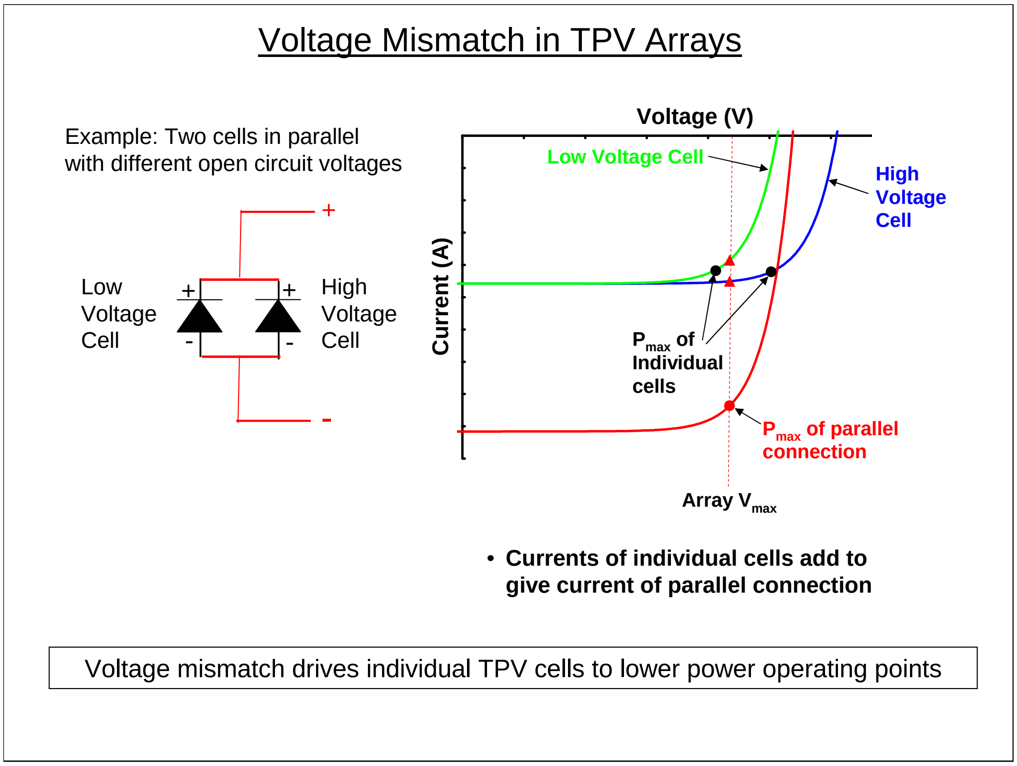
Example: Two cells in series with different light generated current

- **Voltages of individual cells add to give voltage of series connection**

Current mismatch drives individual TPV cells to lower power operating points

Simple illustration of network losses (1) :

This slide shows two current mismatched TPV cells/substrings (individual IV characteristics shown in black) that are connected in series. The red IV curve shows the IV and maximum operating point of the series connected array. Kirchoff's law states that series connected circuits elements have the same current. As can be seen from the graph, when the array is operating at P_{max}, the current restriction (follow red line) forces each individual TPV cell to operate away from it's maximum power point (red triangles vs. black circles). The difference in power is the networking loss.



Voltage Mismatch in TPV Arrays

Example: Two cells in parallel
with different open circuit voltages

- **Currents of individual cells add to give current of parallel connection**

Voltage mismatch drives individual TPV cells to lower power operating points

Simple illustration of network losses (1) :

This slide shows two voltage mismatched TPV cells/substrings (individual IV characteristics shown in black) that are connected in parallel. The red curve shows the array IV and maximum operating point of the parallel connected array. Kirchoff's law requires that parallel connected circuits elements operate at the same voltage. As can be seen from the graph, when the array is operating at P_{max}, the voltage restriction (follow the red line) forces each individual TPV cell to operate away from it's maximum power point (red triangles vs. black circles). The difference in power is the networking loss.

TPV Network Efficiency

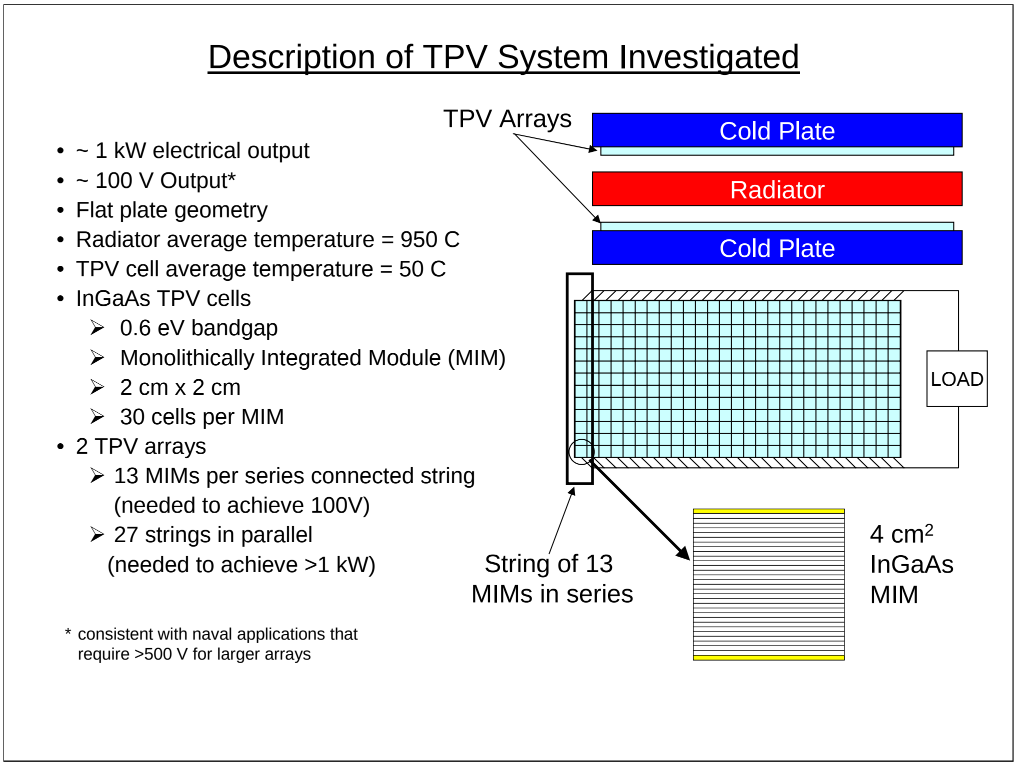
- TPV network efficiency quantifies the amount of power dissipated in the TPV array

$$\eta_{\text{network}} = \frac{\text{Max power output from TPV array}}{\text{Sum of max power output from each individual TPV cell}}$$

- Need to maximize TPV network efficiency (minimize losses) in order to maximize TPV efficiency

Maximum output power from TPV array will be less than
the sum of available power from the individual cells

The definition of networking efficiency is the maximum power that can be delivered to a load from the TPV array, divided by the sum of the available power (i.e. P_{max}) that is available from each of the individual cells prior to interconnection

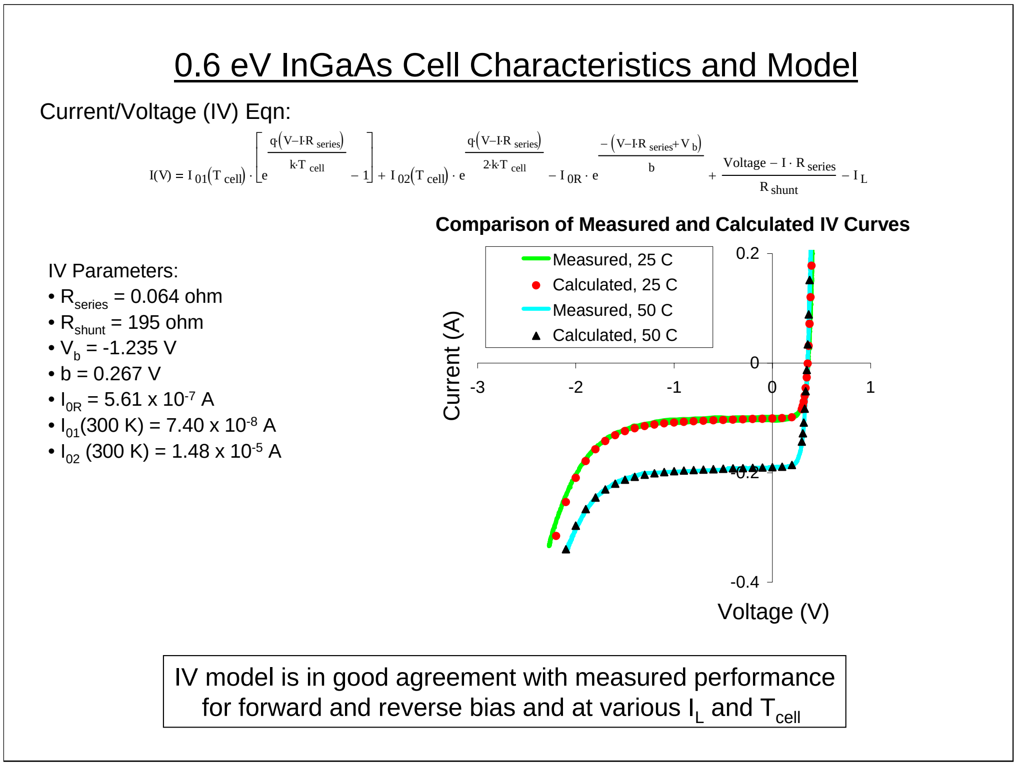


Description of TPV System Investigated

- ~ 1 kW electrical output
- ~ 100 V Output*
- Flat plate geometry
- Radiator average temperature = 950 C
- TPV cell average temperature = 50 C
- InGaAs TPV cells
  - 0.6 eV bandgap
  - Monolithically Integrated Module (MIM)
  - 2 cm x 2 cm
  - 30 cells per MIM
- 2 TPV arrays
  - 13 MIMs per series connected string (needed to achieve 100V)
  - 27 strings in parallel (needed to achieve >1 kW)

* consistent with naval applications that require >500 V for larger arrays

This slide lists the details of the simulated TPV array that is analyzed for this study.



0.6 eV InGaAs Cell Characteristics and Model

Current/Voltage (IV) Eqn:

$$I(V) = I_{01}(T_{cell}) \cdot \left[e^{\frac{q \cdot (V - I \cdot R_{series})}{k \cdot T_{cell}}} - 1 \right] + I_{02}(T_{cell}) \cdot e^{\frac{q \cdot (V - I \cdot R_{series})}{2 \cdot k \cdot T_{cell}}} - I_{0R} \cdot e^{\frac{-(V - I \cdot R_{series} + V_b)}{b}} + \frac{\text{Voltage} - I \cdot R_{series}}{R_{shunt}} - I_L$$

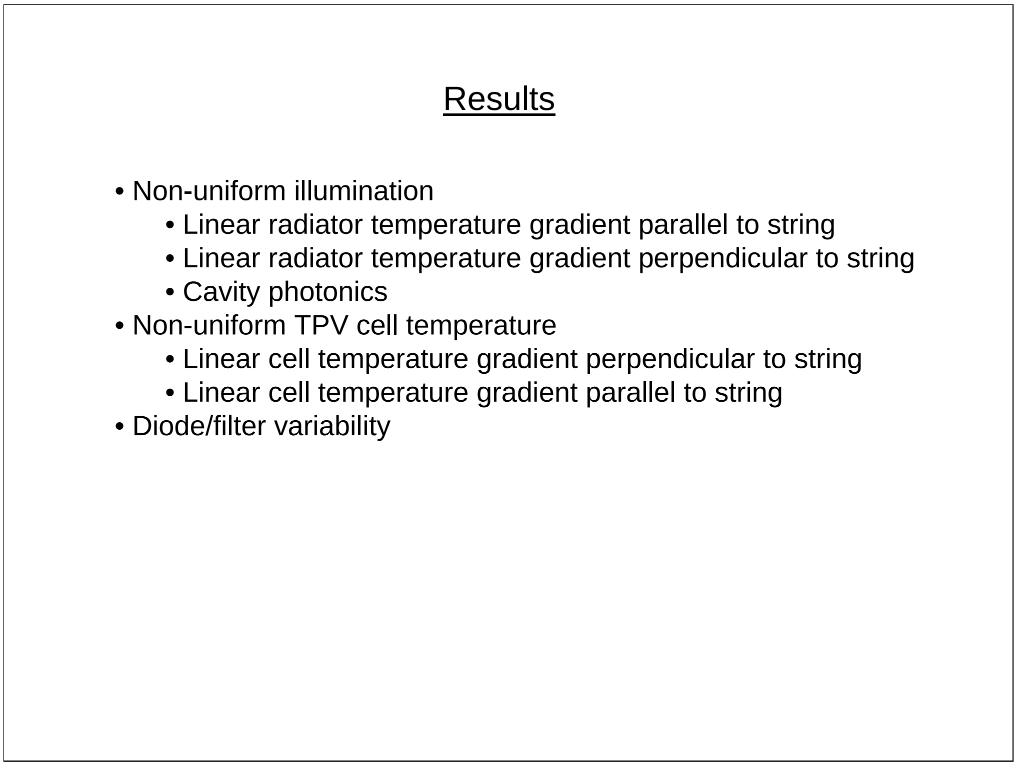
IV Parameters:

- R_{series} = 0.064 ohm
- R_{shunt} = 195 ohm
- V_b = -1.235 V
- b = 0.267 V
- I_{0R} = 5.61 x 10^{-7} A
- I_{01}(300 K) = 7.40 x 10^{-8} A
- I_{02} (300 K) = 1.48 x 10^{-5} A

Comparison of Measured and Calculated IV Curves

IV model is in good agreement with measured performance for forward and reverse bias and at various I_L and T_{cell}

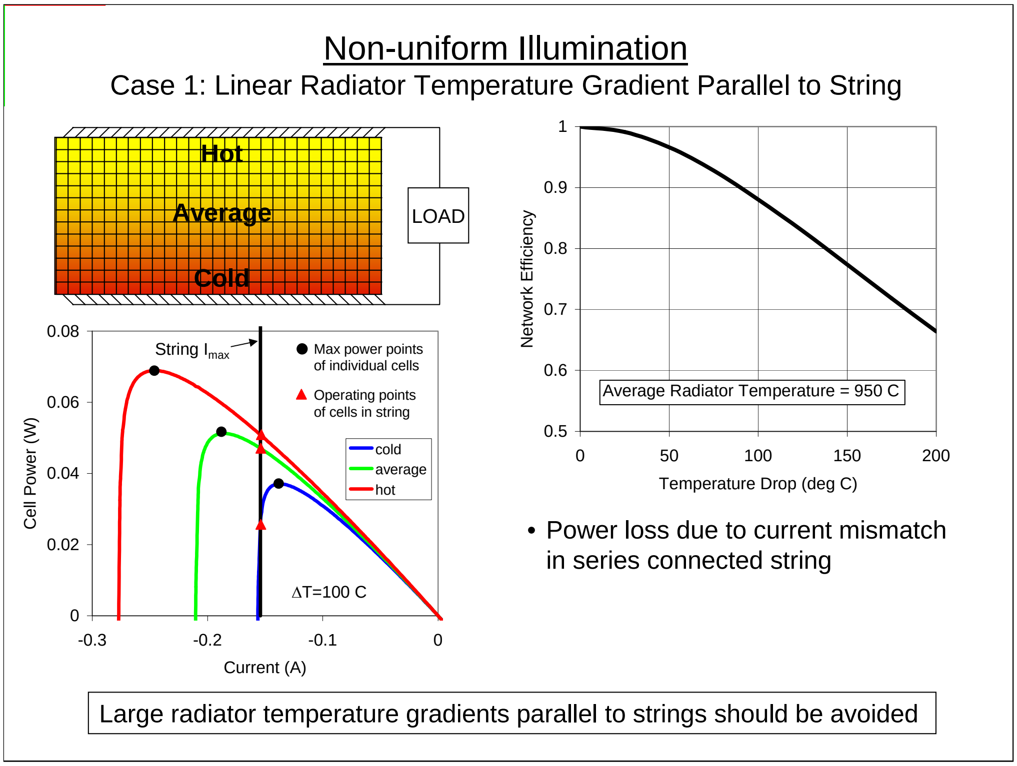
The current-voltage characteristics of the diodes studies in this work were fit to the illuminated IV characteristics of high quality 0.6eV InGaAs MIMs. The MIM area is 2x2 square centimeter. Standard diode mathematical models fit very well to measured data.



Results

- Non-uniform illumination
  - Linear radiator temperature gradient parallel to string
  - Linear radiator temperature gradient perpendicular to string
  - Cavity photonics
- Non-uniform TPV cell temperature
  - Linear cell temperature gradient perpendicular to string
  - Linear cell temperature gradient parallel to string
- Diode/filter variability

The following slides present the modeling results.



Non-uniform Illumination

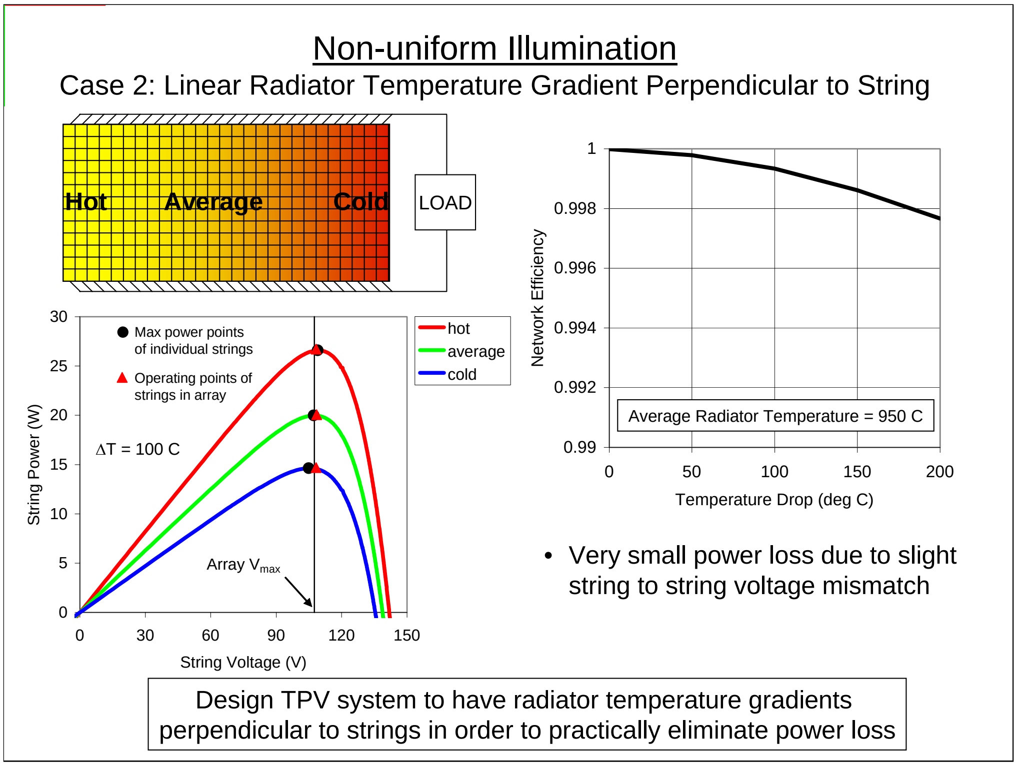
Case 1: Linear Radiator Temperature Gradient Parallel to String

- Power loss due to current mismatch in series connected string

Large radiator temperature gradients parallel to strings should be avoided

A radiator temperature gradient, parallel to the TPV strings was modeled for an ~1kW array of uniform 0.6eV InGaAs TPV MIMs. The average radiator temperature (T) across the area was held constant (i.e. nearly constant heat transfer to the entire array), however a ΔT was modeled, where the gradient is **parallel** to the string direction. The primary result of this radiator temperature gradient is that TPV cells within strings now experience a current mismatch within the string. For radiator temperature gradients greater than 50°C the impact of the current mismatch becomes significant (network efficiency becomes less than 95%).

The bottom left curve illustrates why the networking efficiency degrades with temperature gradients parallel to the string direction. The 3 curves show the Power-Current characteristics of 3 cells within a string, one across from hottest end of the radiator, one in the middle, and one across from the coldest end of the radiator. The maximum available power from each individual cell is shown (black circles). The difference in current mismatch is nearly as factor of two at the ends of each string for large temperature gradients. The array current (I_{max}) corresponding to the maximum power of the array is also shown in the figure. Kirchoff's law forces each of the individual TPV cells within each string to operate at I_{max}; these operating points are significantly different than the individual maximum power points, thus the low networking efficiency.



Non-uniform Illumination

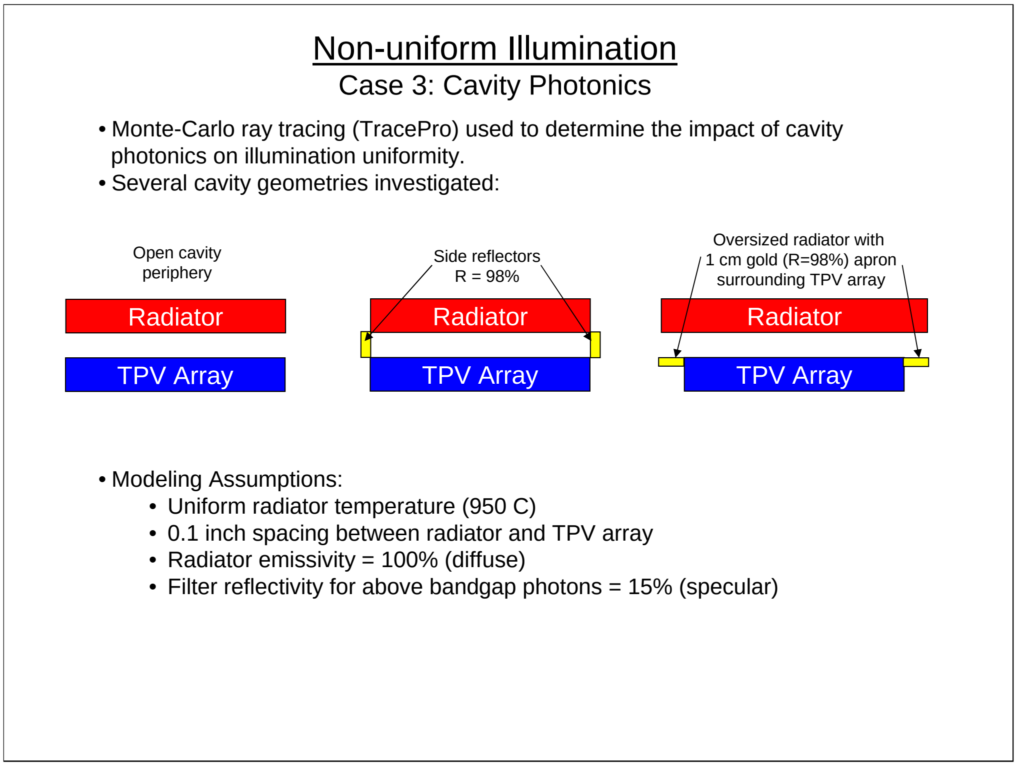
Case 2: Linear Radiator Temperature Gradient Perpendicular to String

- Very small power loss due to slight string to string voltage mismatch

Design TPV system to have radiator temperature gradients perpendicular to strings in order to practically eliminate power loss

The same radiator temperature gradient is modeled again, except in this case the temperature gradient is perpendicular to the TPV string direction. The average radiator temperature (T) again was held constant across the area (i.e. nearly constant heat transfer to the entire array). The ΔT was modeled, with the gradient **perpendicular** to the string direction. The primary result of this radiator temperature gradient is that diodes within each string are now current matched within the string, however the there now exists a voltage mismatch for each of the strings. However the TPV cell voltage is a much more slowly varying function of the incident radiation flux (radiator temperature) than is the current (i.e. logarithmic vs. linear dependence) thus the voltage mismatch is not nearly as great as for the current mismatch in the previous slide. For the radiator temperature gradients considered here impact of the voltage mismatch due to radiator temperature gradients perpendicular to the string direction is not very significant.

The bottom left curve illustrates why the networking efficiency only slightly degrades with large temperature gradients perpendicular to the string direction. The 3 curves show the Power-Voltage characteristics of 3 strings, one across from hottest end of the radiator, one in the middle, and one across from the coldest end of the radiator. The maximum available power from each individual cell is shown (black circles). The difference in voltage mismatch is very small for the three individual strings, despite the large radiator temperature difference. The array voltage (V_{max}) corresponding to the maximum power of the array is also shown in the figure. Kirchoff's law forces each of the individual TPV strings to operate at V_{max}; these operating points are only slightly different than the individual maximum power points, thus the high networking efficiency (>99%).



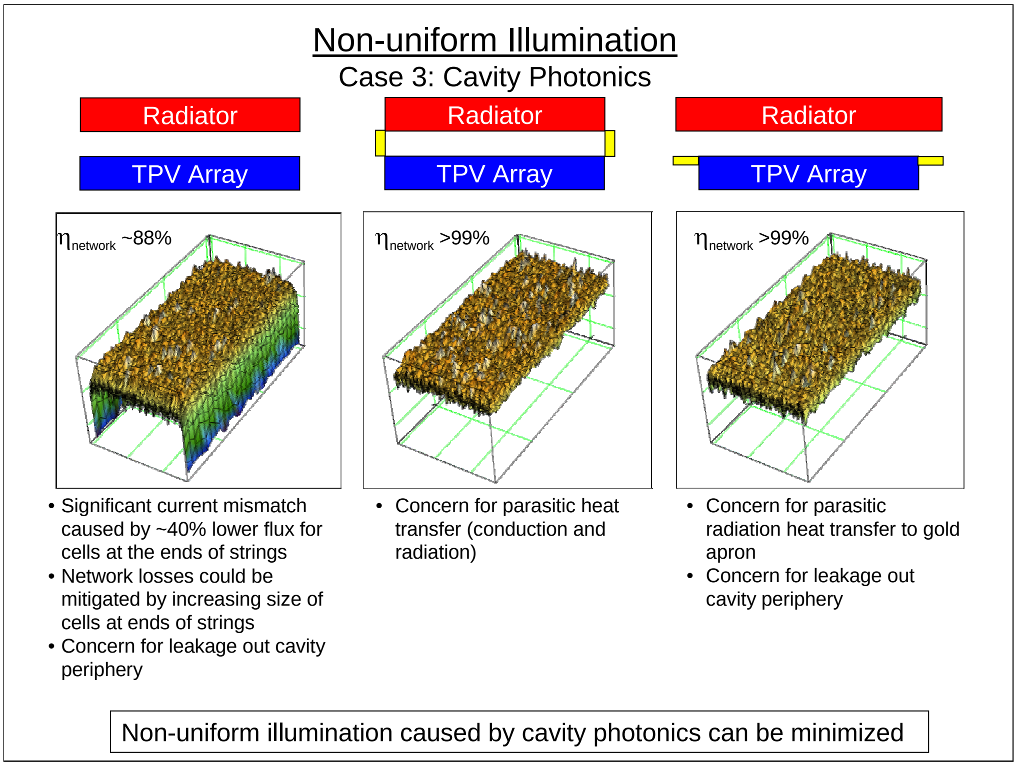
Non-uniform Illumination

Case 3: Cavity Photonics

- Monte-Carlo ray tracing (TracePro) used to determine the impact of cavity photonics on illumination uniformity.
- Several cavity geometries investigated:

- Modeling Assumptions:
  - Uniform radiator temperature (950 C)
  - 0.1 inch spacing between radiator and TPV array
  - Radiator emissivity = 100% (diffuse)
  - Filter reflectivity for above bandgap photons = 15% (specular)

We have modeled the cavity photonics of several typical geometries used for flat plate TPV converters. The three considered in this work are shown in the slide. The first is a finite flat plate geometry separated by a 0.1 inch gap; this geometry results in some photon flux escaping the ends into vacuum and reducing the incident photon flux near the perimeter of the array. The other two geometries model the same flat plate geometry using reflectors to minimize the escaping photon flux (i.e. reflect it back into the cavity). The latter two cavity designs effectively reduces current/voltage mismatch between array elements.



Non-uniform Illumination

Case 3: Cavity Photonics

$\eta_{network}$ ~88%

- Significant current mismatch caused by ~40% lower flux for cells at the ends of strings
- Network losses could be mitigated by increasing size of cells at ends of strings
- Concern for leakage out cavity periphery

$\eta_{network}$ >99%

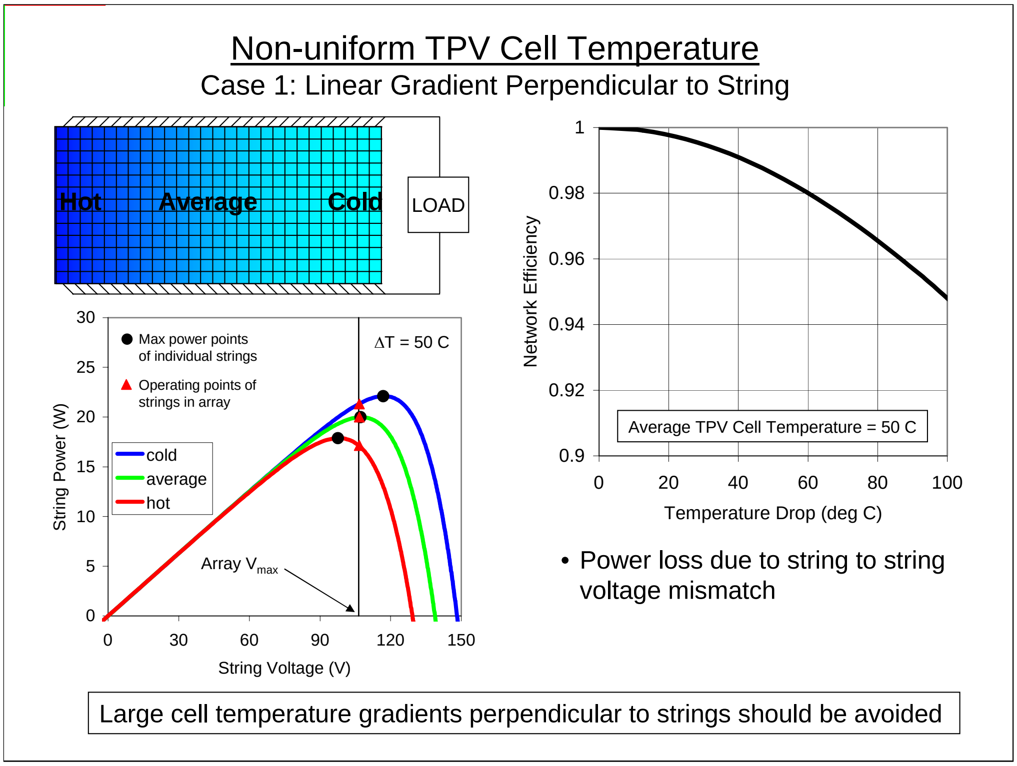
- Concern for parasitic heat transfer (conduction and radiation)

$\eta_{network}$ >99%

- Concern for parasitic radiation heat transfer to gold apron
- Concern for leakage out cavity periphery

Non-uniform illumination caused by cavity photonics can be minimized

These figures show the normalized flux distributions for the three cavity geometries considered. The gold reflector significantly increases the uniformity of the flux distribution across the entire TPV array. By not using any reflectors, nearly 40% lower photon flux losses occur for TPV cells near the array perimeter (resulting in large current mismatch). Gold aprons and reflectors provide nearly uniform photon fluxes across the array.



Non-uniform TPV Cell Temperature

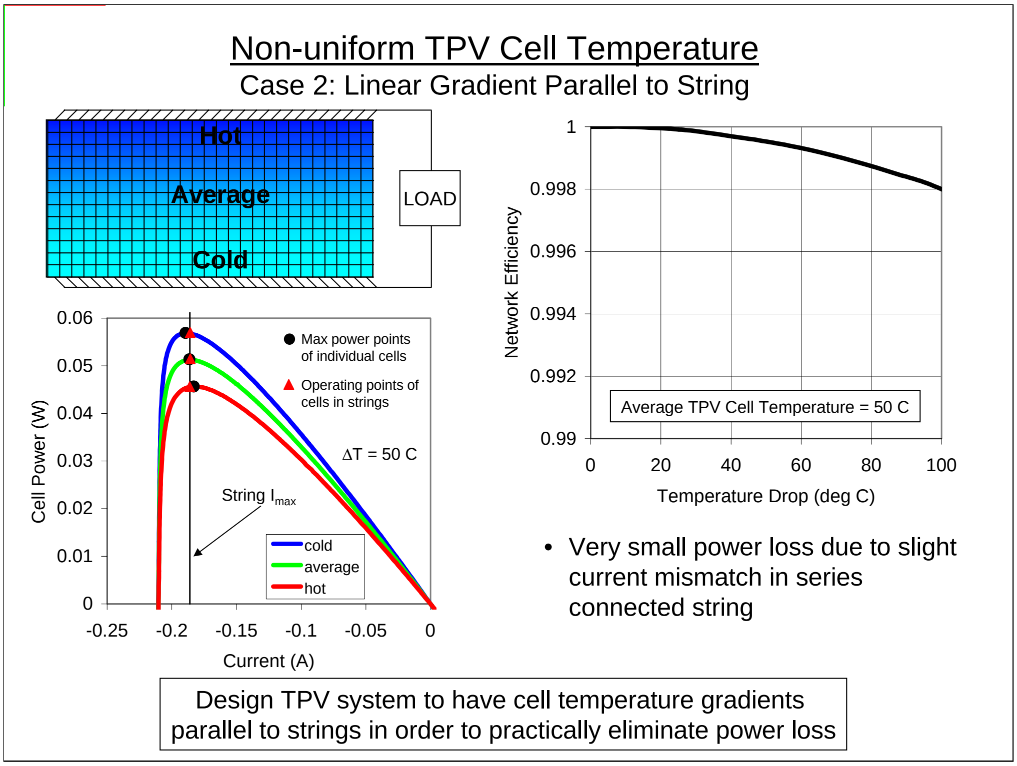
Case 1: Linear Gradient Perpendicular to String

- Power loss due to string to string voltage mismatch

Large cell temperature gradients perpendicular to strings should be avoided

TPV cell operating voltage is sensitive to the diode temperature. As diode temperature increases the cell voltage decreases. Thus a cold side temperature gradient perpendicular to the string direction results in a voltage mismatch between strings. For large temperature gradients across the cold side (>80°C) [holding $T_{\text{average-cold side}}$ constant] the string voltage mismatch become significant enough to degrade network efficiency to less than 95%.

The bottom left curve illustrates why the networking efficiency degrades with large cold side temperature gradients perpendicular to the string direction. The 3 curves show the Power-Voltage characteristics from 3 individual strings, one across from warmest end of the cold plate, one in the middle, and one across from the coldest end of the cold plate. The maximum available power from each individual string is shown (black circles). The array voltage (V_{max}) corresponding to the maximum power of the array is also shown in the figure. Kirchoff's law forces each of the individual TPV strings to operate at V_{max} of the array, these operating points are different than the individual maximum power points, thus the non-ideal networking efficiency.



Non-uniform TPV Cell Temperature

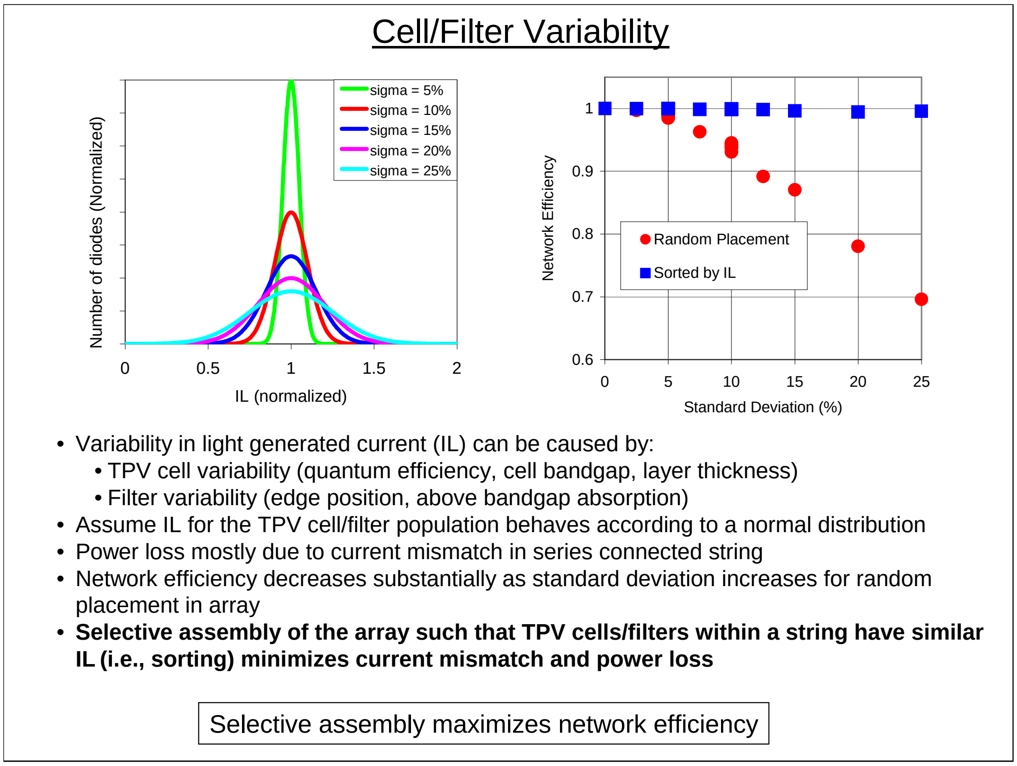
Case 2: Linear Gradient Parallel to String

- Very small power loss due to slight current mismatch in series connected string

Design TPV system to have cell temperature gradients parallel to strings in order to practically eliminate power loss

A cold side temperature gradient parallel to the string direction results in a zero voltage mismatch between strings, and only the slightest mismatch in I_{max} for each cell within a string. For large temperature gradients across the cold side (>80°C) [holding $T_{average\text{-}cold\ side}$ constant] the I_{max} mismatch between cells within the string is so insignificant that network efficiency is greater than 99%% even for 100°C temperature gradients.

The bottom left curve illustrates why the networking efficiency does not effectively degrade even with large cold side temperature gradients parallel to the string direction. The 3 curves show the Power-Current characteristics of 3 cells within a string, one at the warmest end of the cold plate, one in the middle, and one at from the coldest end of the cold plate. The maximum available power from each individual string is shown (black circles). The array current (I_{max}) corresponding to the maximum power of the array is also shown in the figure. Kirchoff’s law forces each of the individual TPV cells to operate at I_{max}; these operating points are negligibly different than the individual maximum power points, thus the near ideal networking efficiency.

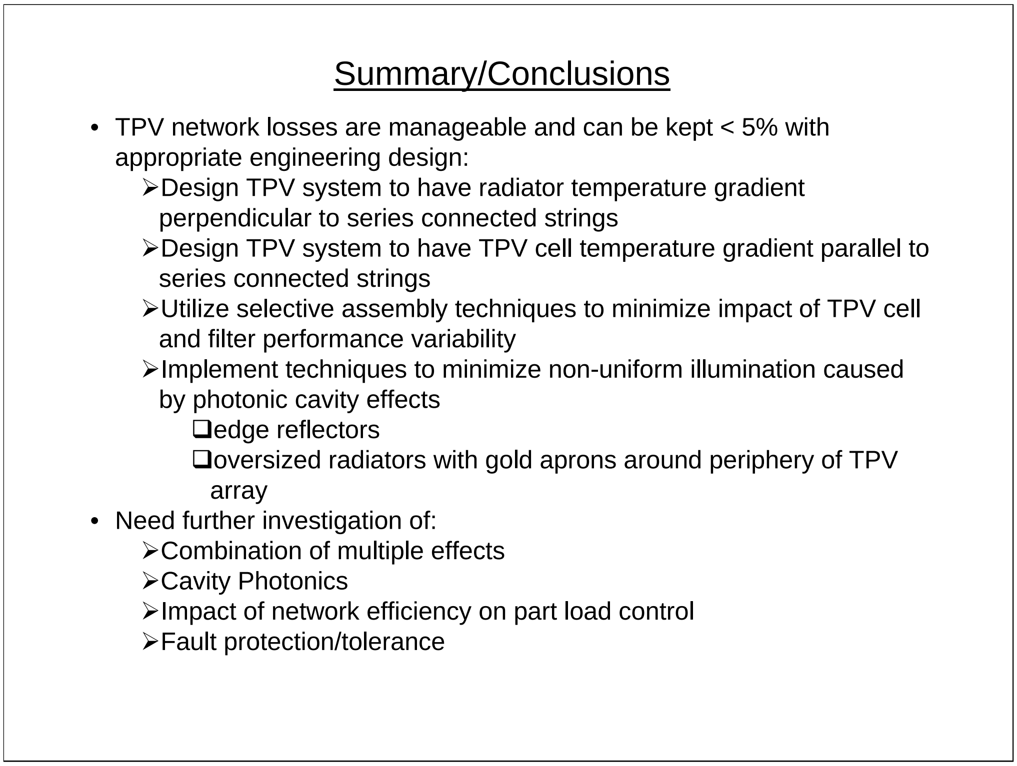


Cell/Filter Variability

- Variability in light generated current (IL) can be caused by:
  - TPV cell variability (quantum efficiency, cell bandgap, layer thickness)
  - Filter variability (edge position, above bandgap absorption)
- Assume IL for the TPV cell/filter population behaves according to a normal distribution
- Power loss mostly due to current mismatch in series connected string
- Network efficiency decreases substantially as standard deviation increases for random placement in array
- **Selective assembly of the array such that TPV cells/filters within a string have similar IL (i.e., sorting) minimizes current mismatch and power loss**

Selective assembly maximizes network efficiency

We next investigated the influence of current mismatch due to manufacturing variability of the individual TPV cells (diode and/or filters) assuming uniform radiator temperature. A large standard deviation in cell current can cause significant networking losses due to current mismatches in series interconnected strings for randomly placed cells (red points). This network loss can be effectively negated by sorting TPV cells to be current matched within strings (see blue points in graph). This sorting/selection procedure results only in slight voltage mismatch between strings and thus near unity network efficiency.

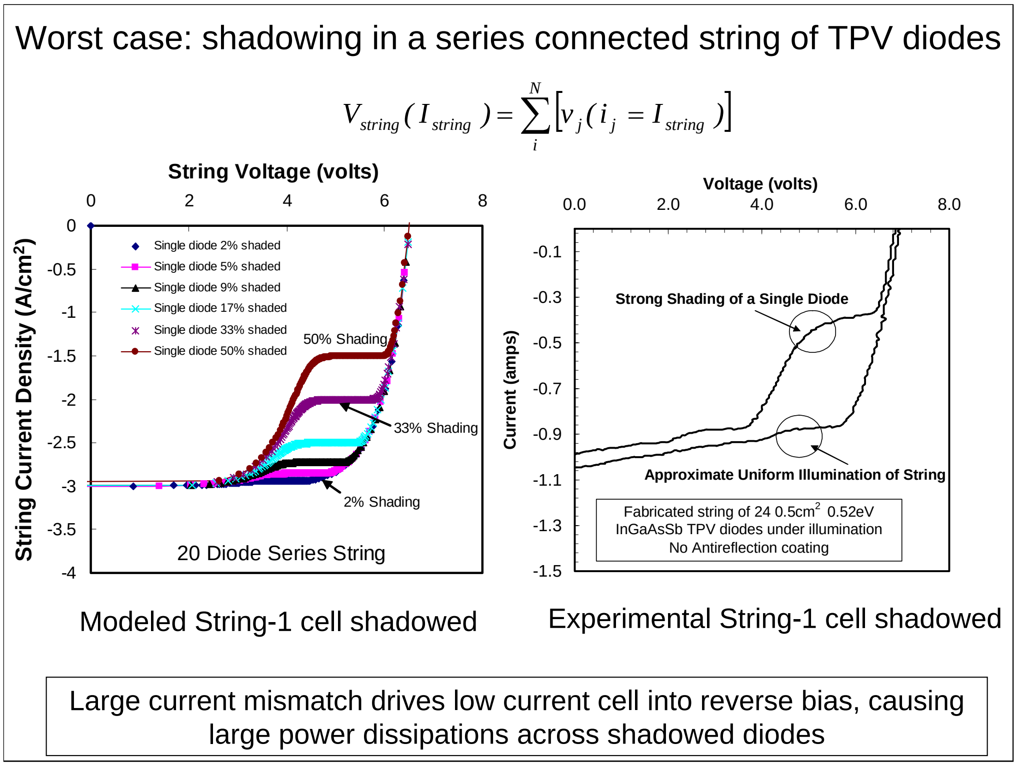


Summary/Conclusions

- TPV network losses are manageable and can be kept < 5% with appropriate engineering design:
  - Design TPV system to have radiator temperature gradient perpendicular to series connected strings
  - Design TPV system to have TPV cell temperature gradient parallel to series connected strings
  - Utilize selective assembly techniques to minimize impact of TPV cell and filter performance variability
  - Implement techniques to minimize non-uniform illumination caused by photonic cavity effects
    - edge reflectors
    - oversized radiators with gold aprons around periphery of TPV array
- Need further investigation of:
  - Combination of multiple effects
  - Cavity Photonics
  - Impact of network efficiency on part load control
  - Fault protection/tolerance

We conclude that networking efficiencies of greater than 95% can be achieved by proper array design, placement, and optical cavity designs. The presence of temperature gradients requires a preferential layout of TPV strings to be perpendicular to hot side temperature gradients and parallel with cold side temperature gradients. Selective assembly greatly negates losses associated with TPV cell variability.

End of Presentation



Worst case: shadowing in a series connected string of TPV diodes

$$V_{string}(I_{string}) = \sum_{i}^{N}\left[v_j(i_j = I_{string})\right]$$

Modeled String-1 cell shadowed

Experimental String-1 cell shadowed

Large current mismatch drives low current cell into reverse bias, causing large power dissipations across shadowed diodes

This additional slides illustrates the influence of strong shadowing of a single TPV cell in a small string of series interconnected diodes. The left figure is predicted behavior and the right hand figure is experimental.