Theory and Practice of Solar Cells: A Cell to System Perspective

How a Module gets its Stripes: Thin Film

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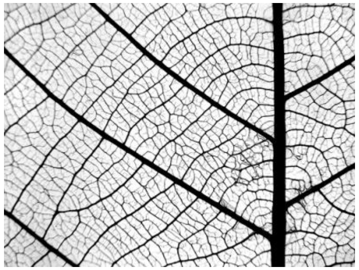
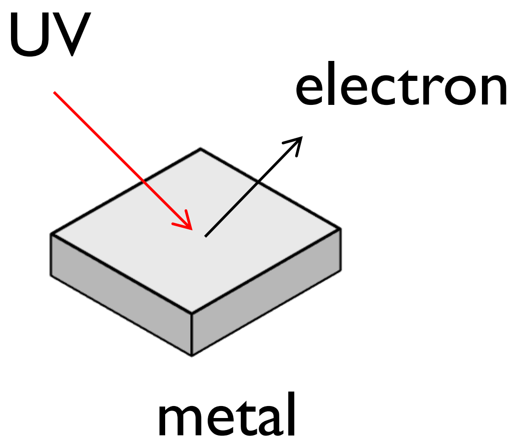


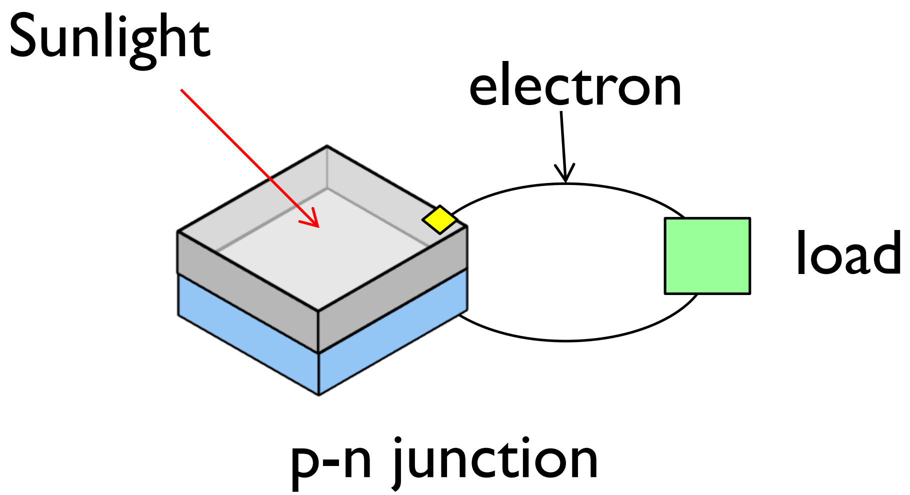
Network for Photovoltaic Technology

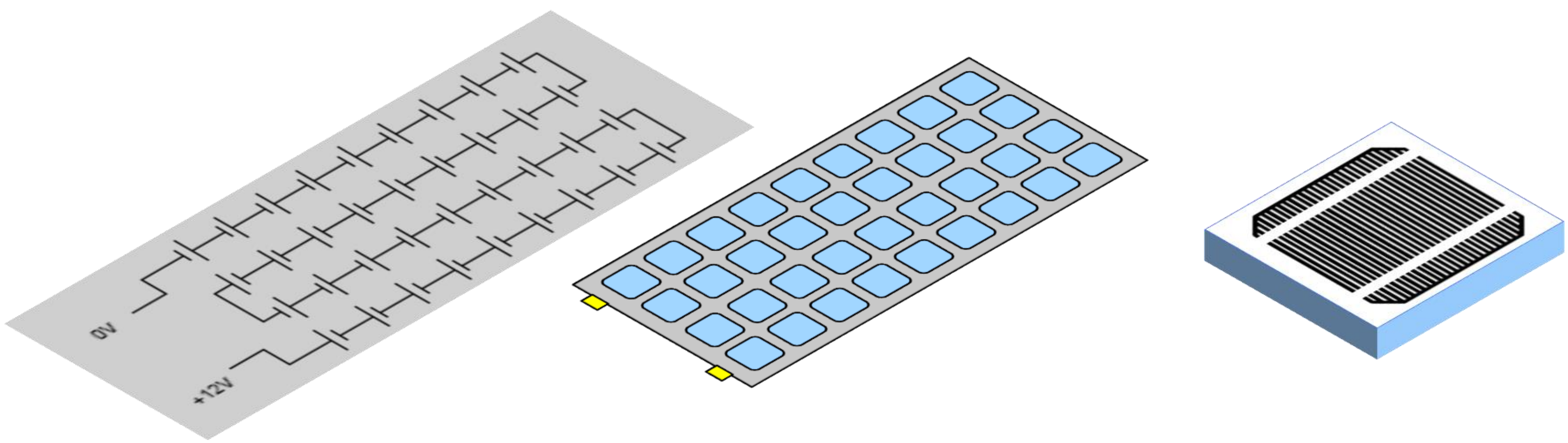
Outline

1) Motivation: Power-loss vs. area loss
2) Theory of power loss
3) Power loss in series-connected cells
4) Cell geometry and power-loss
5) Conclusions

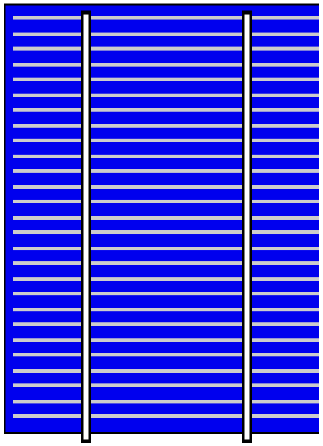
Photoelectric effect and solar cells

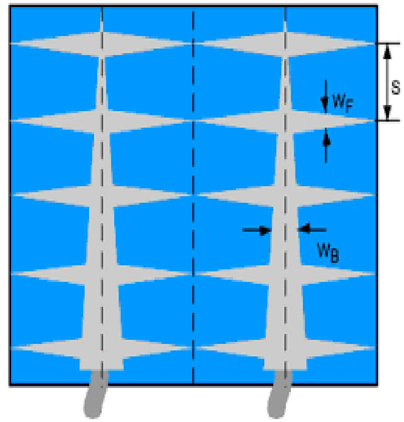


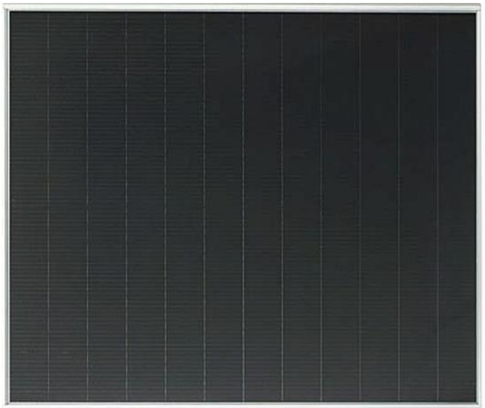


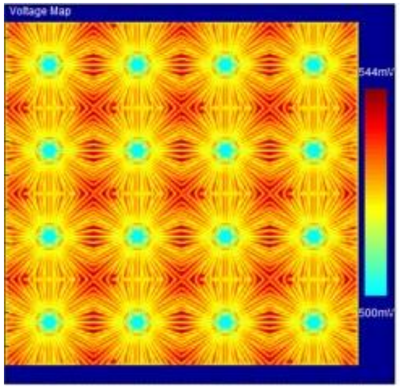


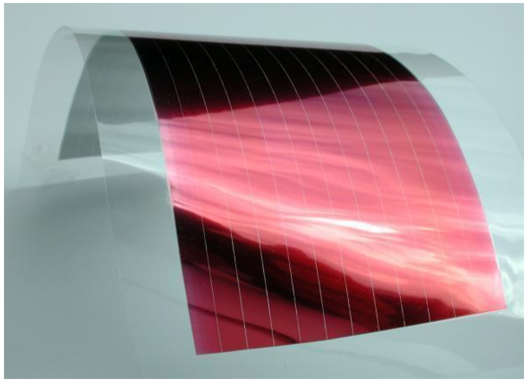
The Puzzle of Striping

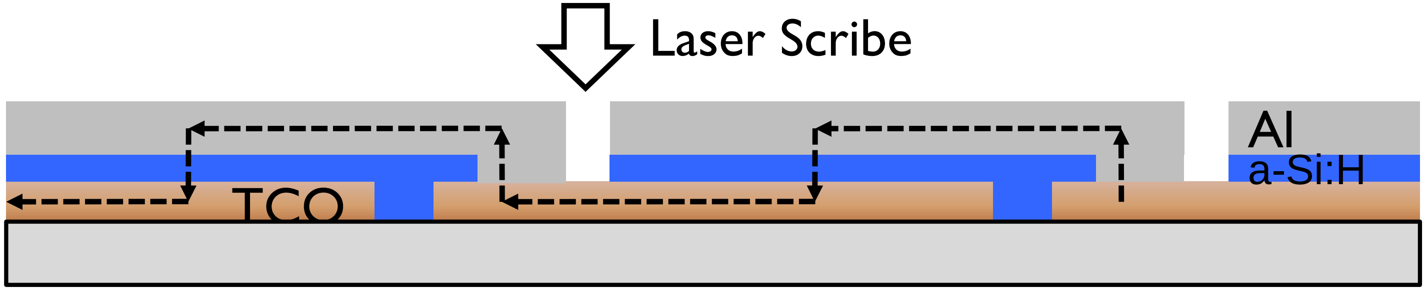


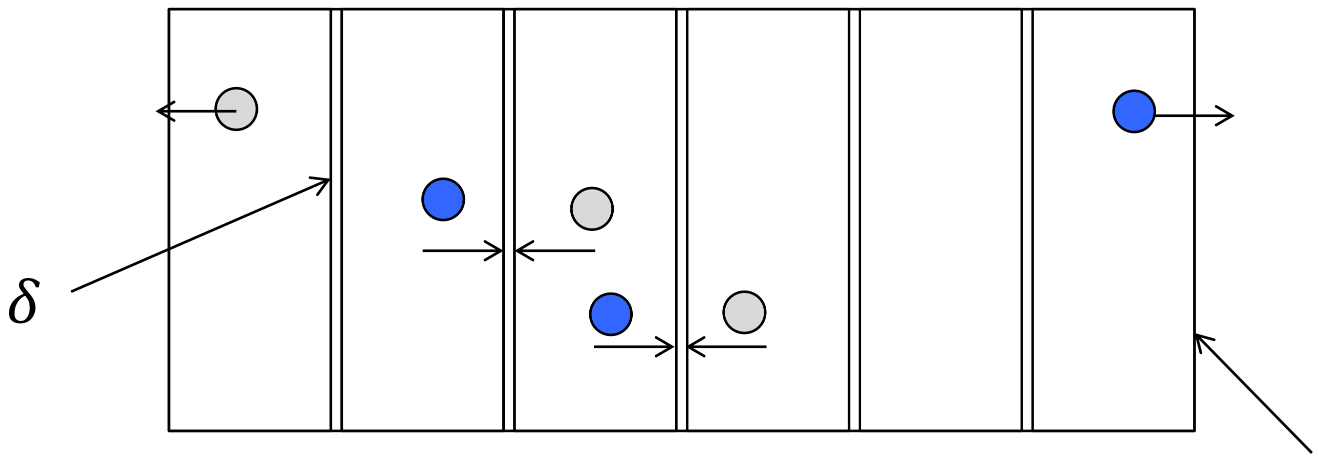


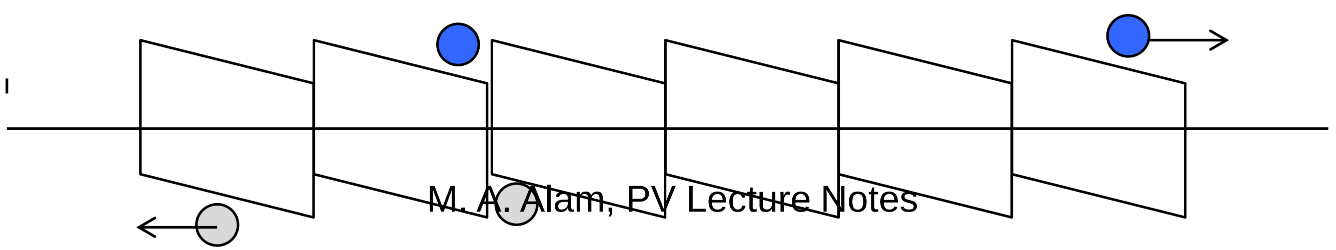







Laser Scribe
Al
a-Si:H
TCO

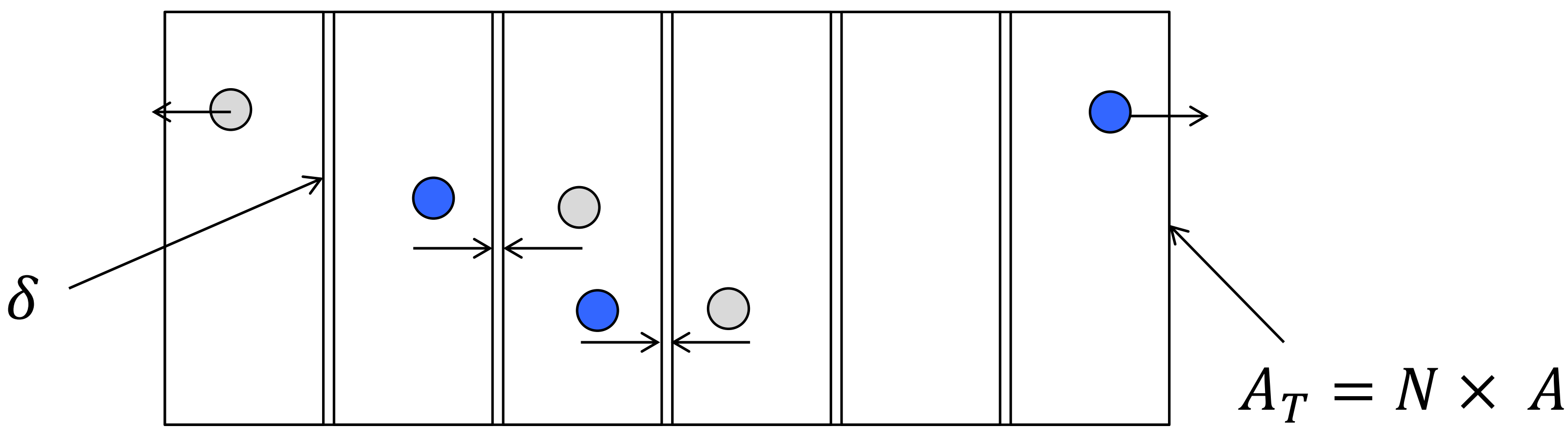

δ



The Puzzle of Striping

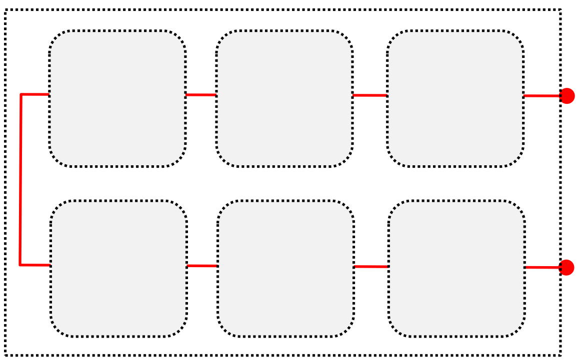
$$P = \left(\frac{I}{N}\right) \times (V \times N) = C_0$$

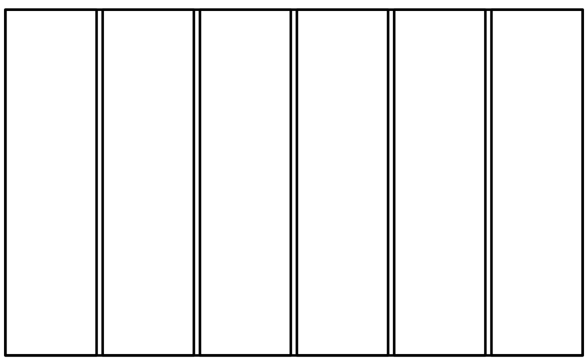
$$P_{area} = (N-1)\delta \times L \sim C_2 N$$

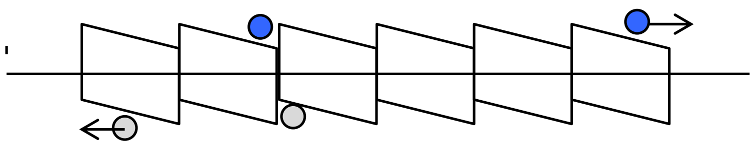


We do striping to reduce series resistance …

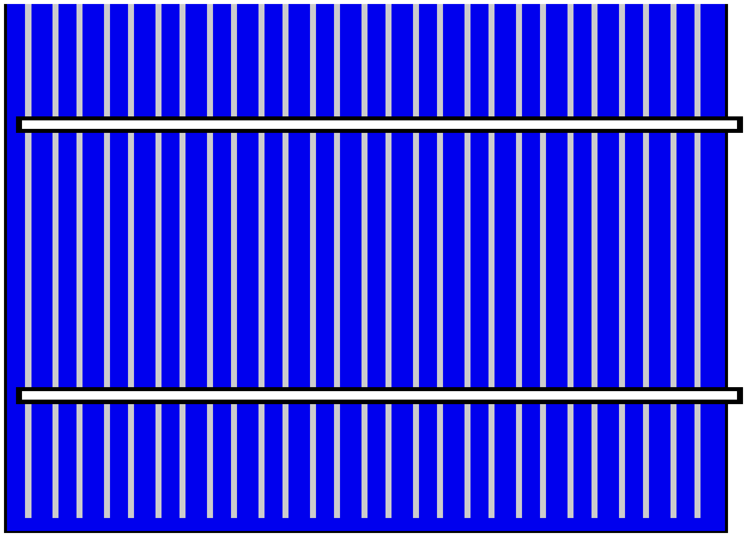
Modules have cells connected in series

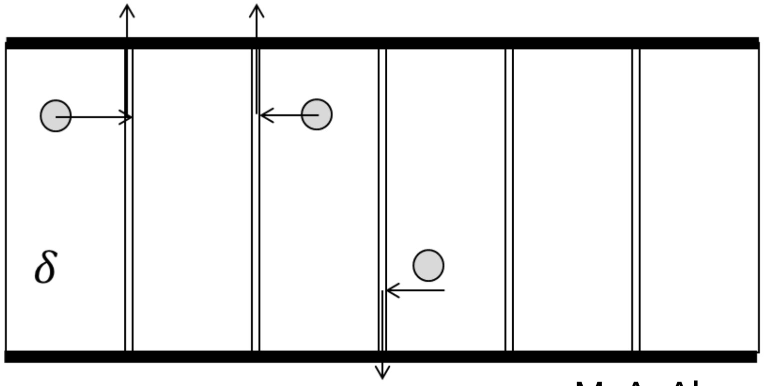




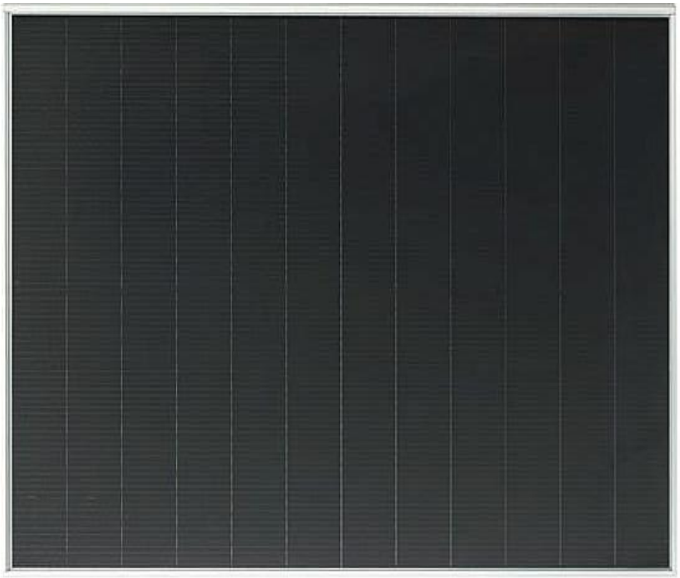


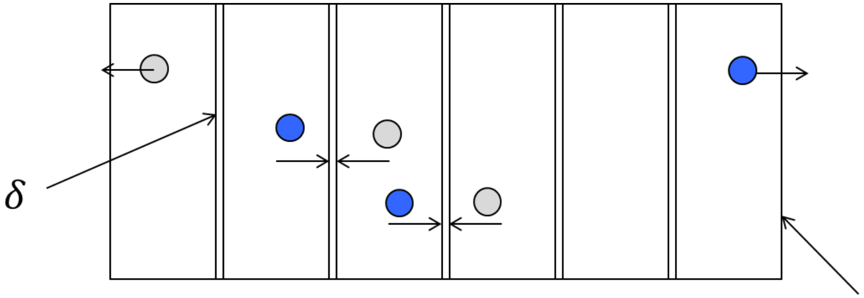
c-Silicon





a-silicon

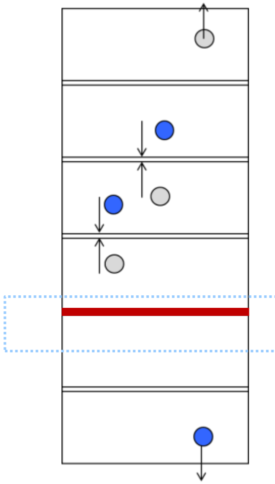




*Google Images

Outline

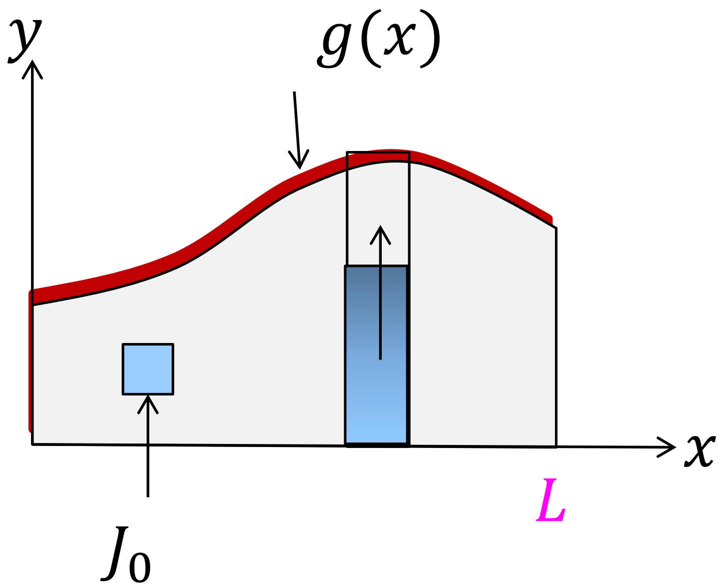
Thin film solar cells:
the case for rectangular cells



ρ in ohms

$$P = \int_0^L dx \int_0^{g(x)} dy\,(J_0 \times y)^2\,\rho$$

Top view



$$\frac{P}{J_0^2 \rho} \equiv P_0 \int_0^L dx\,\frac{g^3(x)}{3}$$

$$A = \int_0^L g(x)dx$$

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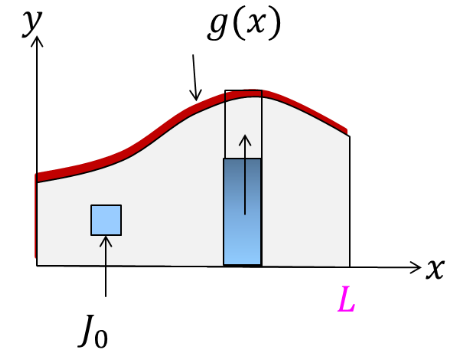
Lagrange optimization

$$\mathbf{L} = J_0^2 \rho \int_0^L dx \frac{g^3(x)}{3} - \lambda^2 \{ \int_0^L g(x) dx - A \}$$

λ^2 is the Lagrange multiplier …



$$\frac{d\mathbf{L}}{dg} = 0 \quad g(x) = 2\lambda/(J_0^2 \rho)$$

$$A = \int_0^L g(x) dx = \frac{2\lambda L}{J_0^2 \rho} \quad \rightarrow \lambda = \frac{A(J_0^2 \rho)}{2L} = const$$

$\rightarrow A/L = const.$ Rectangles perform the best …

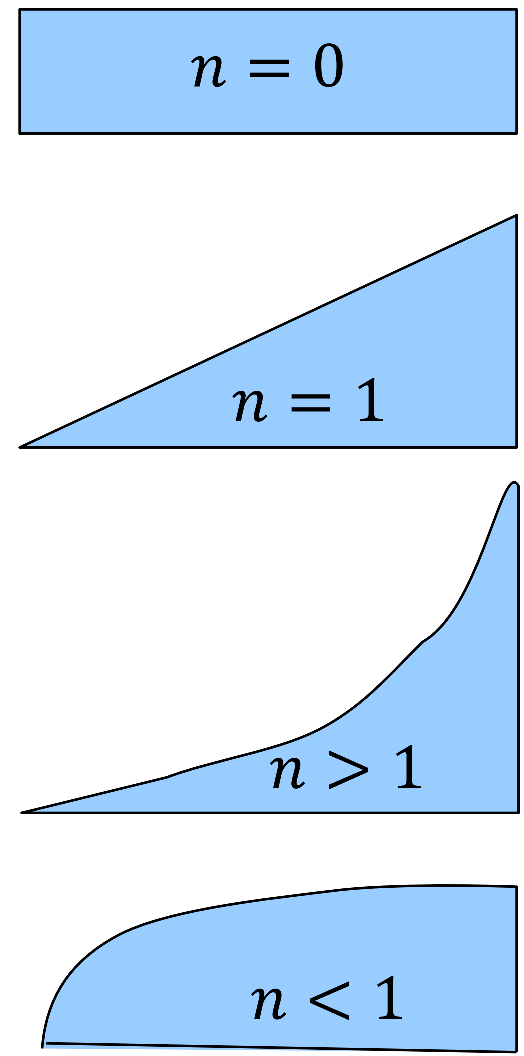
Power Loss in Rectangular Cells

$$P_0 \equiv P/J_0^2\rho = \int_0^L dx \frac{g^3(x)}{3}$$

Let $g(x) = ax^n$ define the shape,
where $a = (n+1)A/L^{n+1}$
ensures that $A = \int_0^L g(x)\, dx$ =const

$$P_o(n) = \frac{(n+1)^3}{3(3n+1)} \times \frac{A^3}{L^2}$$

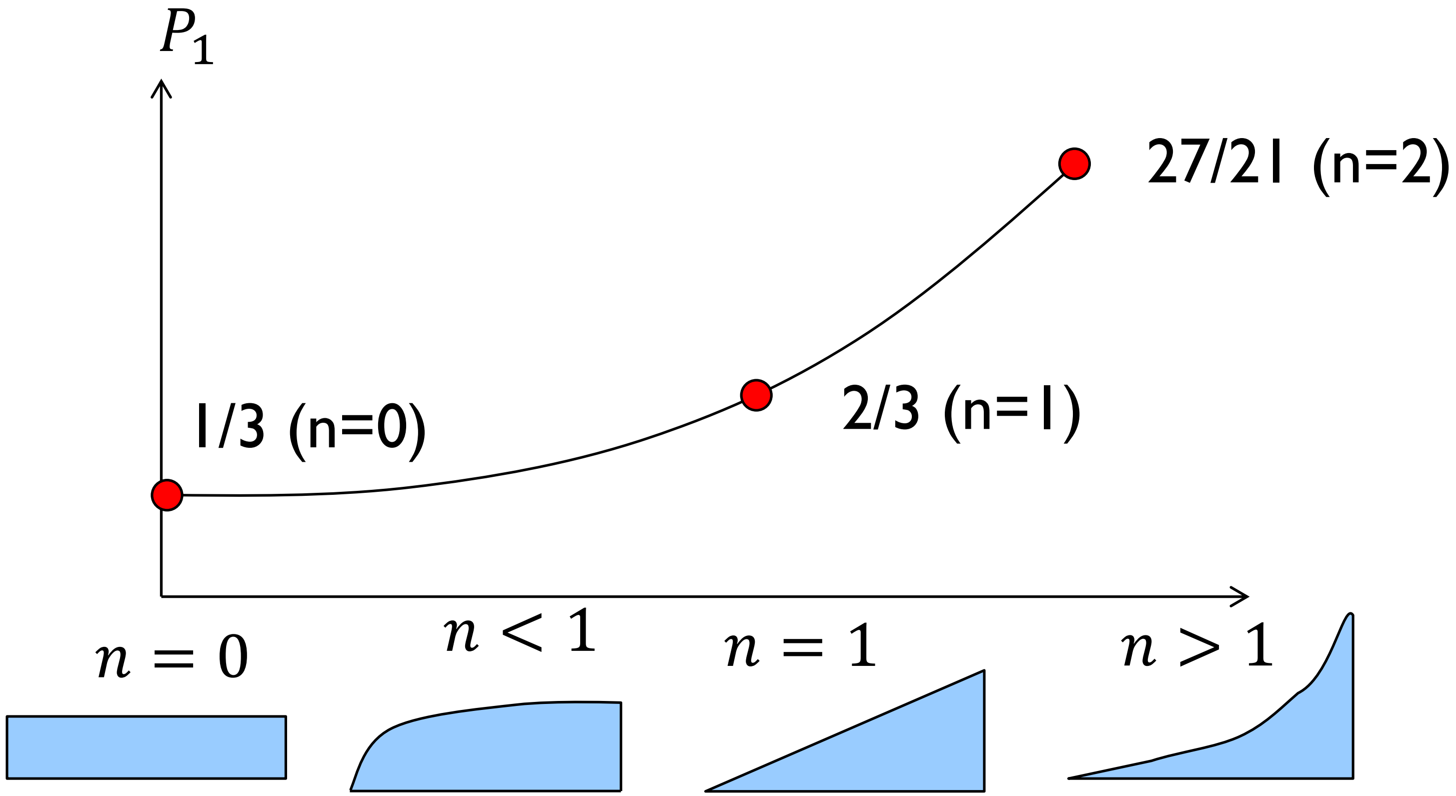
$$P_o(n) \times (L^2/A^3) = \frac{(n+1)^3}{3(3n+1)}$$



Shape and Loss

$$P_o(n) = \frac{(n+1)^3}{3(3n+1)} \times \frac{A^3}{L^2}$$

$$P_1 \equiv P_o(n) \times (L^2/A^3) = \frac{(n+1)^3}{3(3n+1)}$$



Observation 0:

$$P_1 \equiv P_o(n) \times (L^2/A^3) = \frac{(n+1)^3}{3(3n+1)}$$

Power dissipation reduces with the cube of the area, so segmenting a module in many cells is a good idea.

Making the cells longer is also helpful. Given the constraint of the total module area.

The scribe area penalty will be discussed later.

Optimum number of cells

$$P_j = P_o \times N = (J_0^2 \rho) \times \frac{(n+1)^3}{3(3n+1)} \times \left(\frac{A^3}{L^2}\right) \times N$$

$$= (J_0^2 \rho) \times \frac{(n+1)^3}{3(3n+1)} \times \left(\frac{A_T}{N}\right)^3 (N/L^2) = c_1/N^2$$

$$P_{scribe} = (N-1)\delta \times L \times P_{ideal}/A_T \sim C_2 N$$

$$P_{ideal} = \left(\frac{I_{mp}}{N}\right) \times \left(V_{mp} \times N\right) = C_0$$

Optimum number of cells

$$P_j = c_1/N^2 \qquad P_{ideal} = C_0 \qquad P_{scribe} \sim C_2 N$$

$$P_{out} = P_{ideal} - P_j - P_{scribe}$$

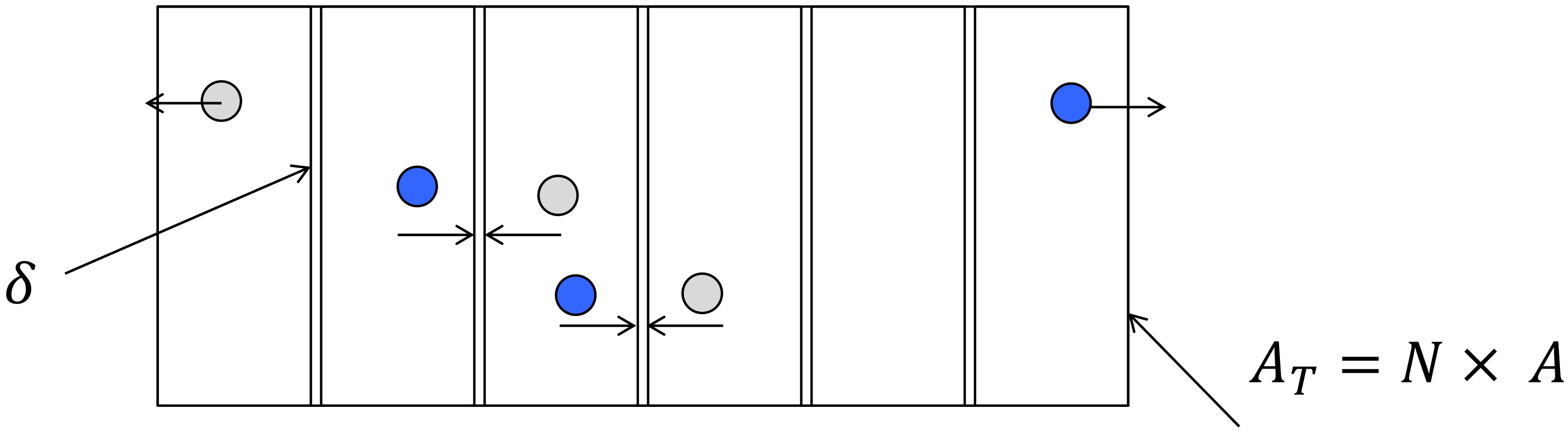
$$= C_0 - C_1/N^2 - c_2 N$$

$$N_{opt} = (2C_1/c_2)^{\frac{1}{3}}$$

Optimum number of cells

$$N_{opt} = (2C_1/C_2)^{\frac{1}{3}}$$

$$= (n+1) \times \left(\frac{A_T}{L}\right) \times \left(\frac{2/3}{(3n+1)}\right)^{\frac{1}{3}} \times \left(\frac{J_0^2 \rho}{C_0 \delta / A_T}\right)^{\frac{1}{3}}$$



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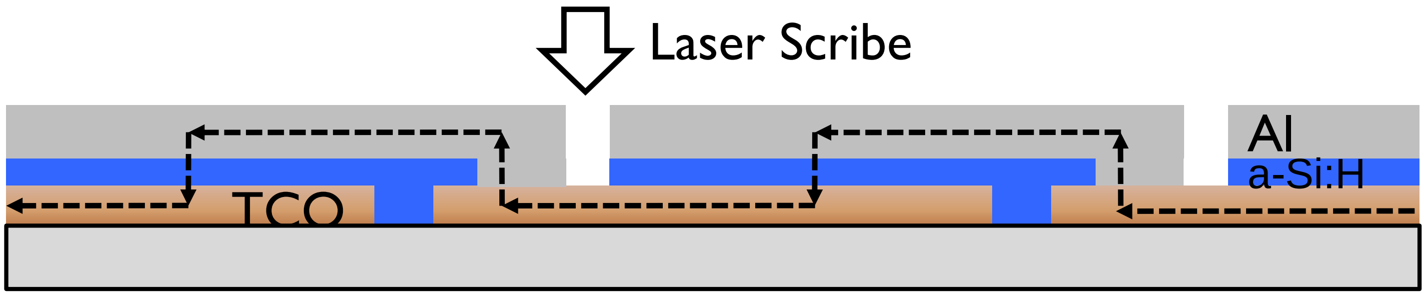
Optimum Cell-size: Compared

Same ITO, same n

$$\frac{N_{opt,1}}{N_{opt,2}} = \left(\frac{J_{0,1}^2/C_{0,1}}{J_{0,2}^2/C_{0,2}}\right)^{\frac{1}{3}} = \left(\frac{J_{0,1}^2/\eta_1}{J_{0,2}^2/\eta_2}\right)^{\frac{1}{3}} = \left(\frac{W_2}{W_1}\right)$$

Technology	J_0	W (cm)
C-Si	40	0.52
a-Si	16	1.18
CIGS	35	0.75
CdTe	26	Homework

Series Connection in Thin Film Cells



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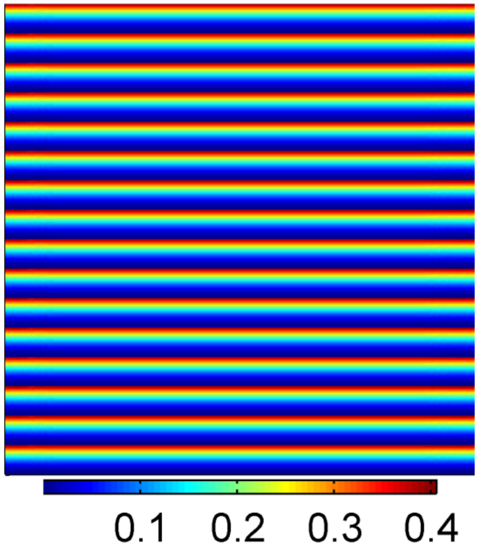
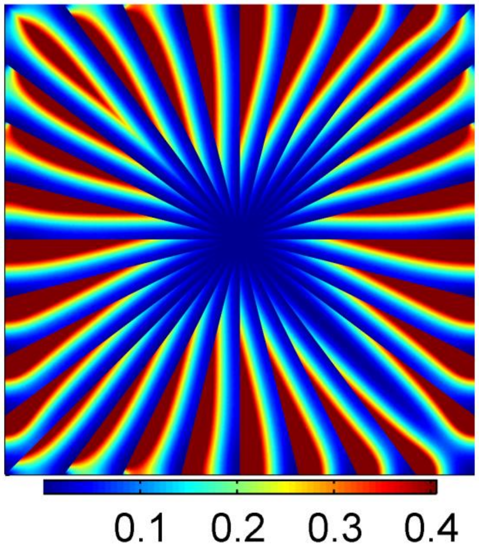
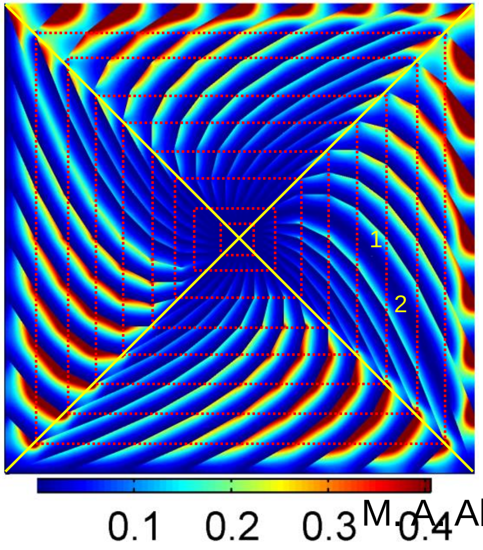
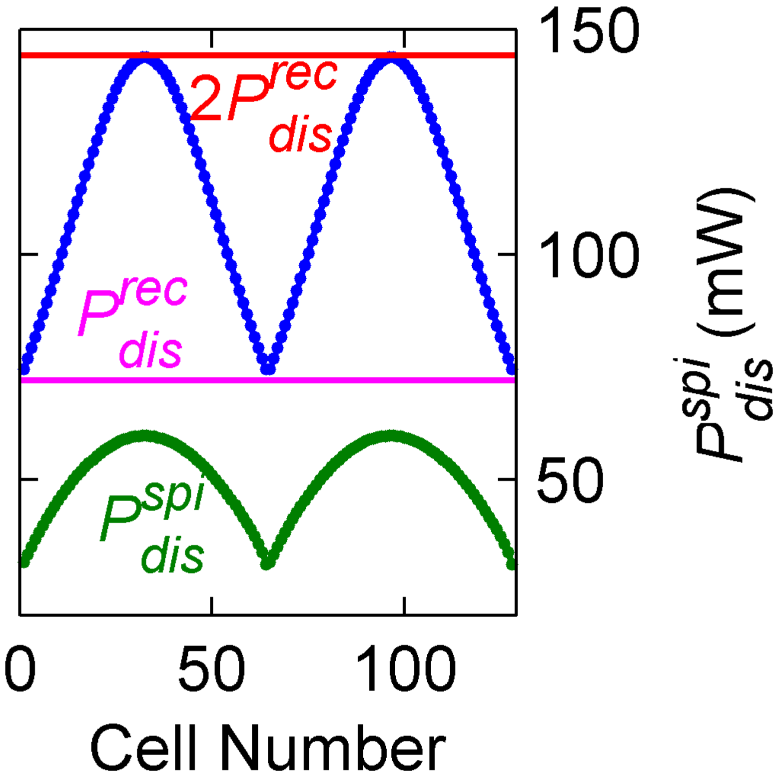
Striping and Shadow Degradation









Optimum number of cells: Two shapes

Same shape:

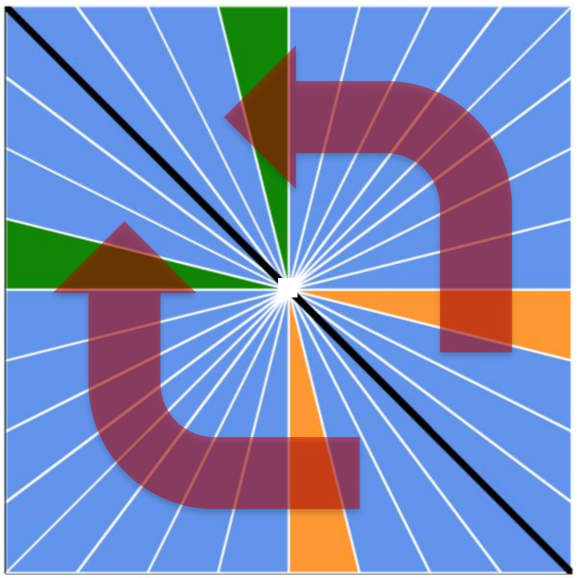
$$\frac{N_{opt,1}}{N_{opt,2}} = \left(\frac{J_{0,1}^2/\eta_1}{J_{0,2}^2/\eta_2}\right)^{\frac{1}{3}} = \left(\frac{W_2}{W_1}\right)$$

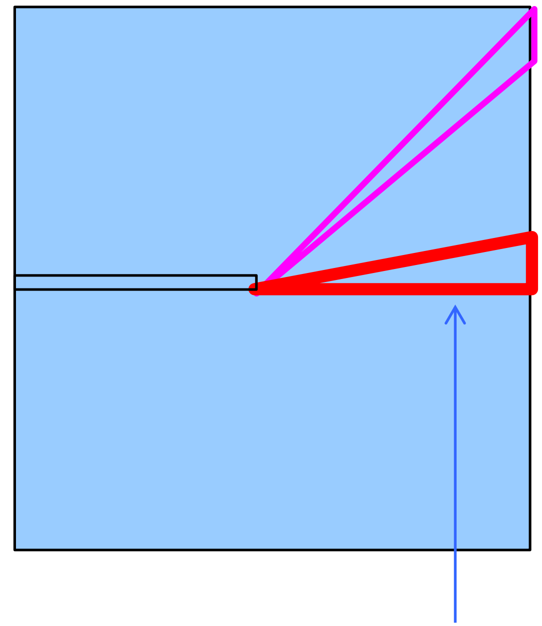
Different shapes (n=0 and n=2/3)

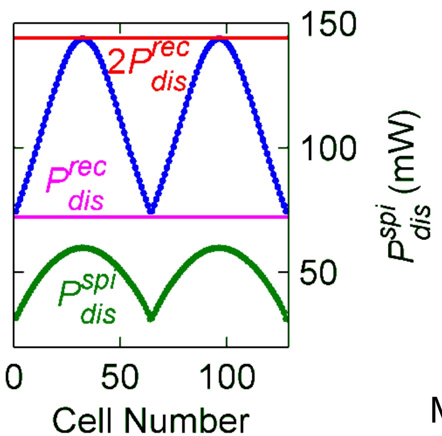
$$\frac{N_{opt,2}}{N_{opt,1}} = (n+1) \times \left(\frac{1}{3n+1}\right)^{\frac{1}{3}} \left(\frac{L_0}{L_n}\right)$$

$$= 1.66 \times \left(\frac{1}{3}\right)^{\frac{1}{3}} \left(\frac{2}{\pi}\right) = 0.735$$

Observation 1: Shorter triangles are dangerous

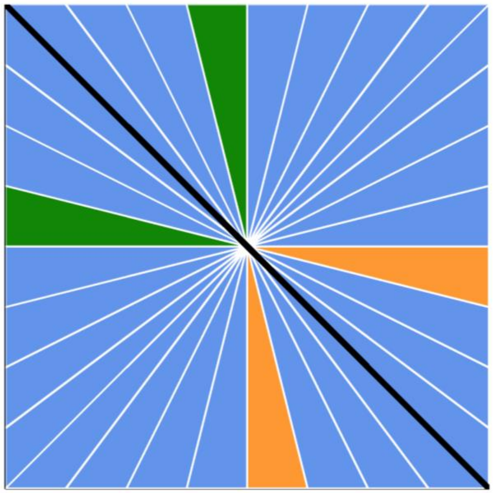


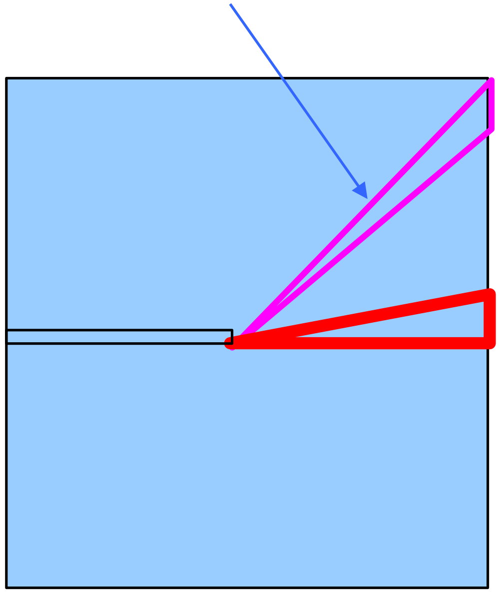


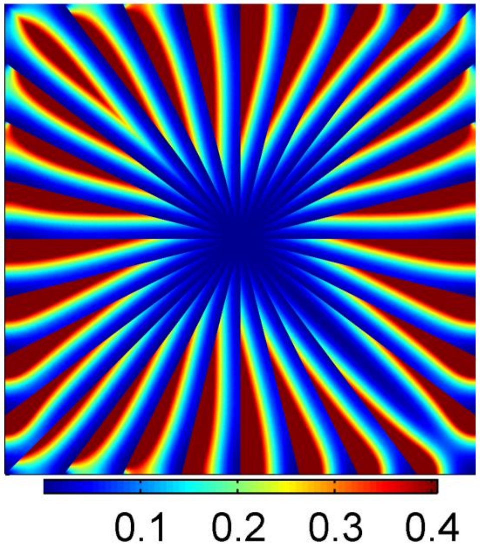


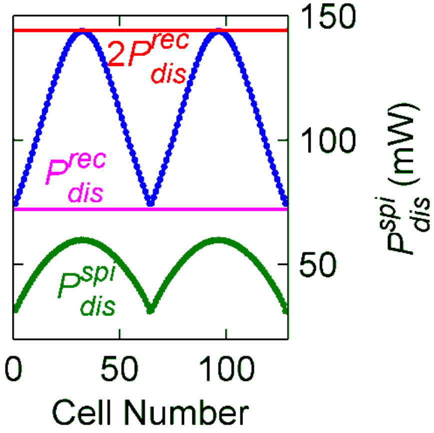
$$\frac{P_1(n=1, L=b)}{P_1(n=0, L=b)} = \frac{\frac{2}{3}}{\frac{1}{3}} = 2$$

Observation 2: Diagonal Triangle Reduces Power





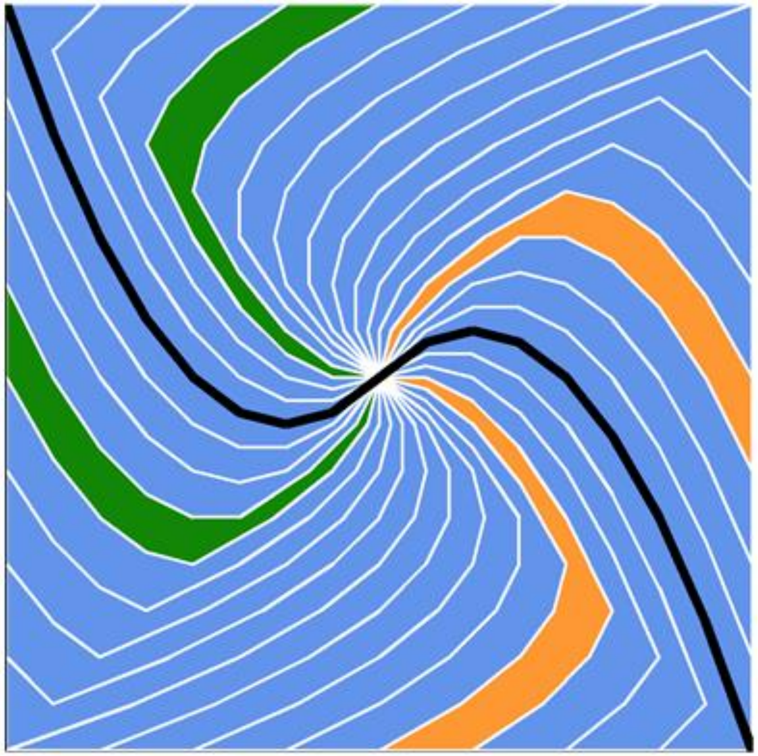




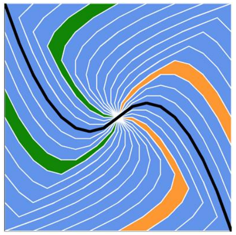
$$P_o = \frac{(n+1)^3}{3(3n+1)} \times \left(\frac{A^3}{L^2}\right)$$

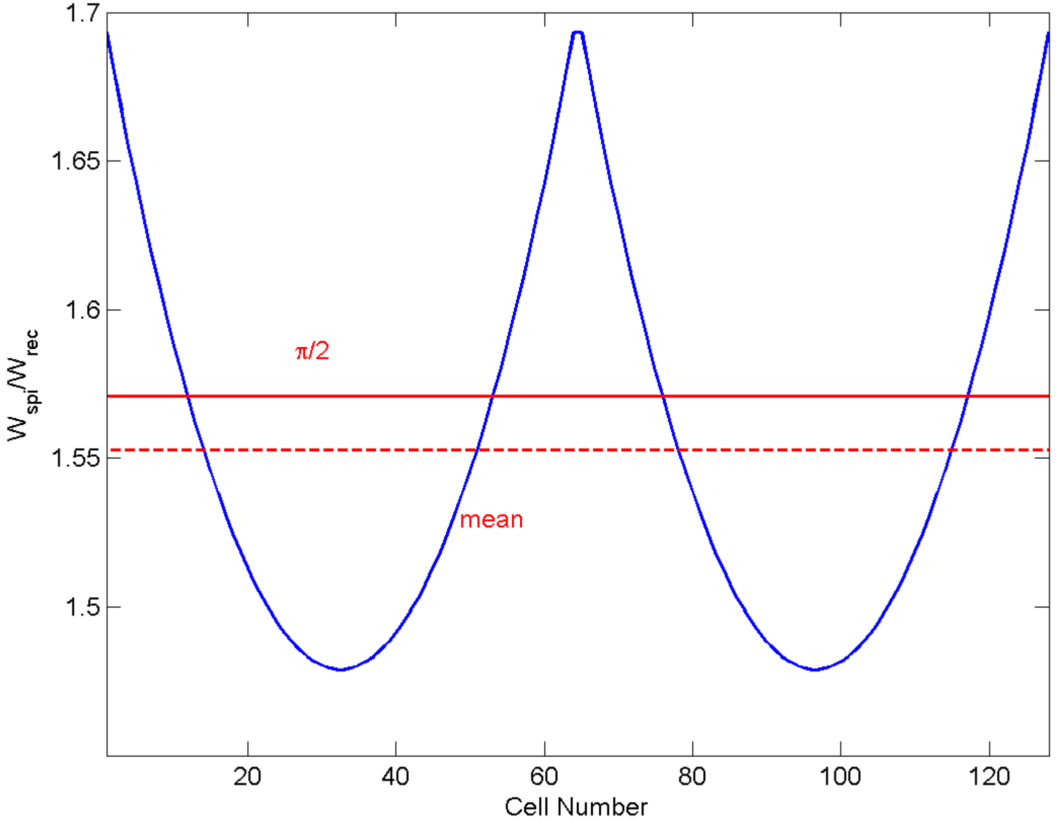
$$\frac{P_o\left(n = 1, L \to \sqrt{2}b\right)}{P_0(n = 0, L = b)} = 1!$$

Design of spiral cells

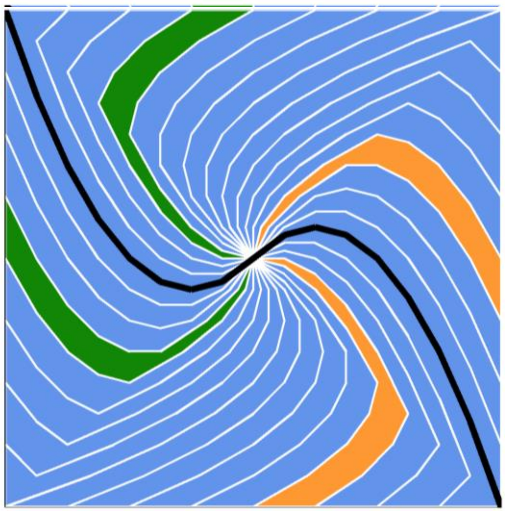


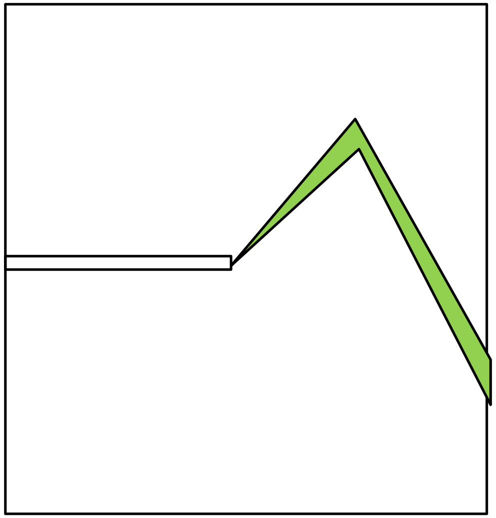
Average Length: $L \sim \pi/2$

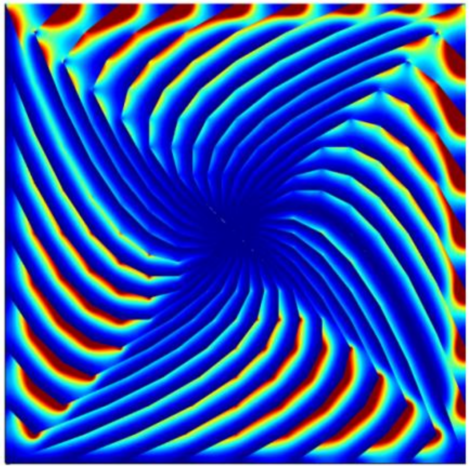


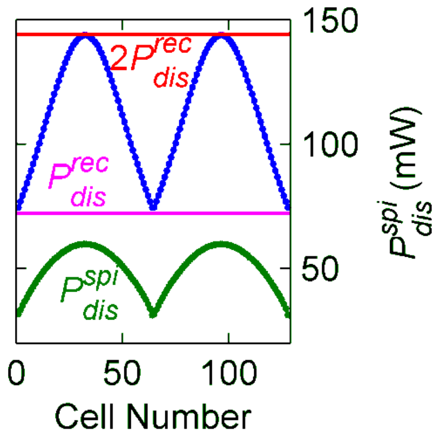


Observation 3: Spirals are long triangles!





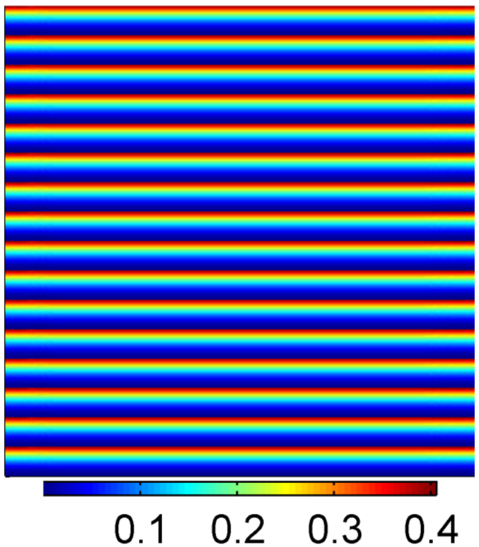


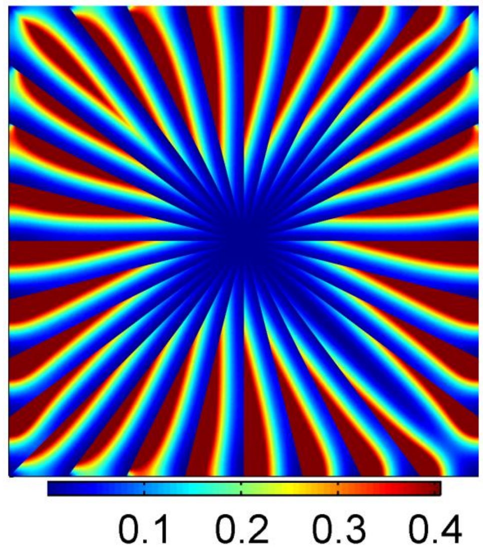


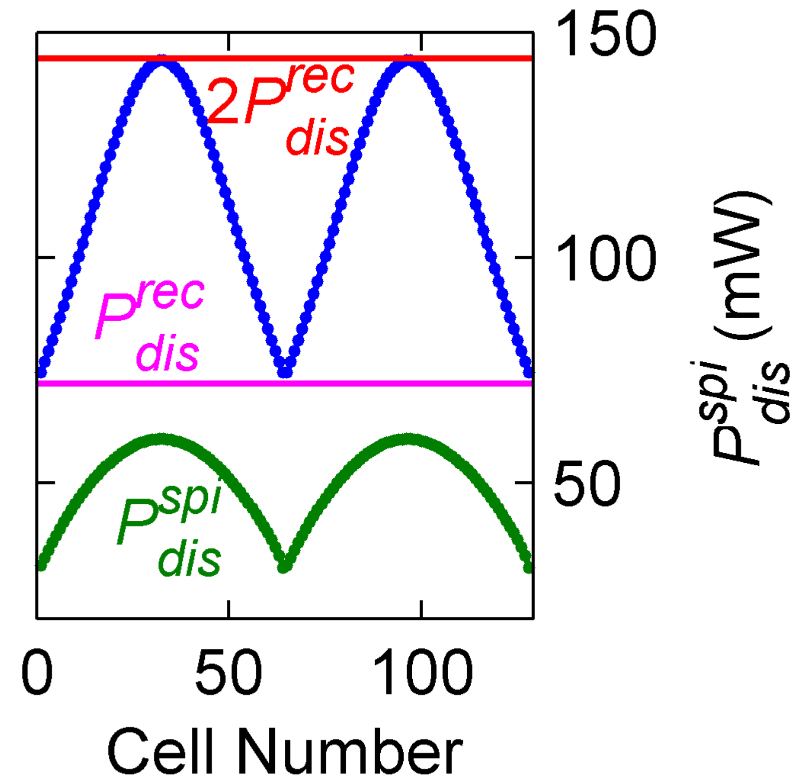
$$P_o = \frac{(n+1)^3}{3(3n+1)} \times \left(\frac{A^3}{L^2}\right)$$

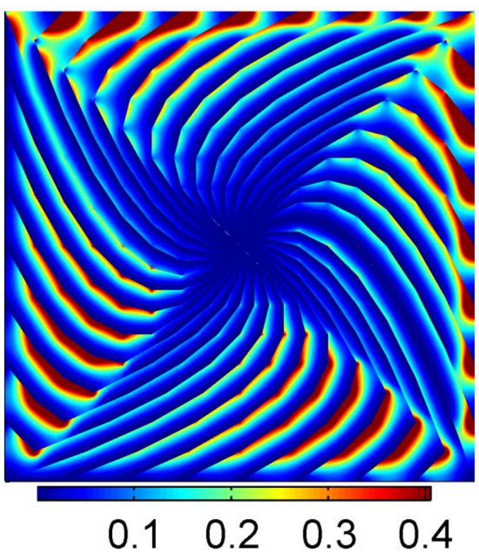
$$\frac{P_o(n \sim 2/3, L \rightarrow (\pi/2)b)}{P_0(n=0, L=b)} < 1!$$

Striping and Shadow Degradation









Each radial and spiral have slightly different dissipation
Spiral design improves the performance by reducing the distance travelled

Conclusions

1) Grids allows one to reduce power-loss due to series resistance.
2) An optimum grid balances shadowing loss and series-resistance losses.
3) Grid spacing also depends on absorber materials.
4) Mathematically, spiral designs are optimum. In practice, grids are rectangular.

Self-assessment

1. The power loss of a thin-film solar cell increases as the (a) first power, (b) second power, (c) third power, or (d) fourth power of the module area.

2. Compare the power dissipation of two types of cells: n=0 and n=2.

3. What is the ratio of the optimum number of cells for CdTe and Perovskite cells.

4. The power dissipation of a module scales inversely as the (a) first power, (b) second power, (c) third power, and (d) fourth power of the width of the cell (L).

5. Spiral cells reduce power dissipation by increasing (L) by (a) 20% (b) 50%, (c) 100%, and (d) 200% compared to a traditional cells.

6. Mention three limitations of the spiral design compared to traditional design.