Quantum Cascade Laser based Mid-IR Photonics: an enabling technology for the “Internet of Things” ?

In search for the killer application of Mid-ir Photonics: from QCLs to Emissive Energy Harvesters

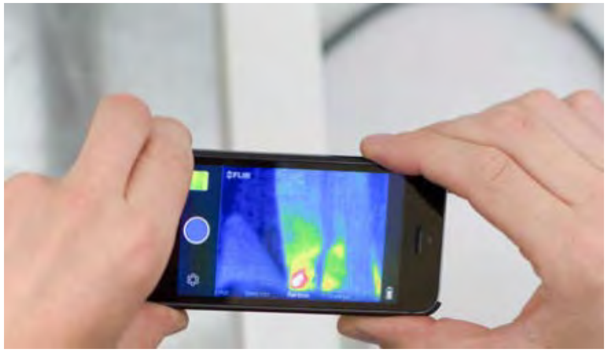
Federico Capasso

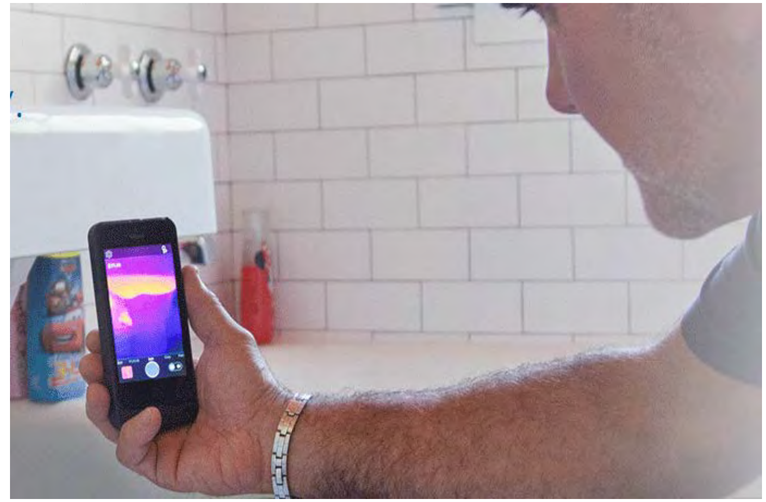
Harvard University, Cambridge

- Are QCL’s are on their way to create the killer application?
- QCLs have saved semiconductor lasers from “band-gap slavery”. **Solar cells are also band-gap slaves**
- Can we invent a new device that generates DC power from the huge amount of mid-ir power emitted by the earth (10^{17} Watts) ? **Yes!**

Collaborators: S. Byrnes, R. Blanchard

An Affordable LWIR Camera in Your Phone





FLIR ONE - Infrared Accessory - fits Apple iPhone 5/5s - See the Heat - (Space Gray)

Product Details

See the world in a new light, even when there's no light at all. The FLIR ONE(TM) personal thermal imager by FLIR® lets you "See the Heat".

- *Manufactured by:* FLIR
- *Merchant SKU:* 435-0001-01-00
- Compatible with Apple iPhone5 and 5s.
- Translates thermal energy into dynamic color images.
- Use for security, home repairs, outdoor activities and more.

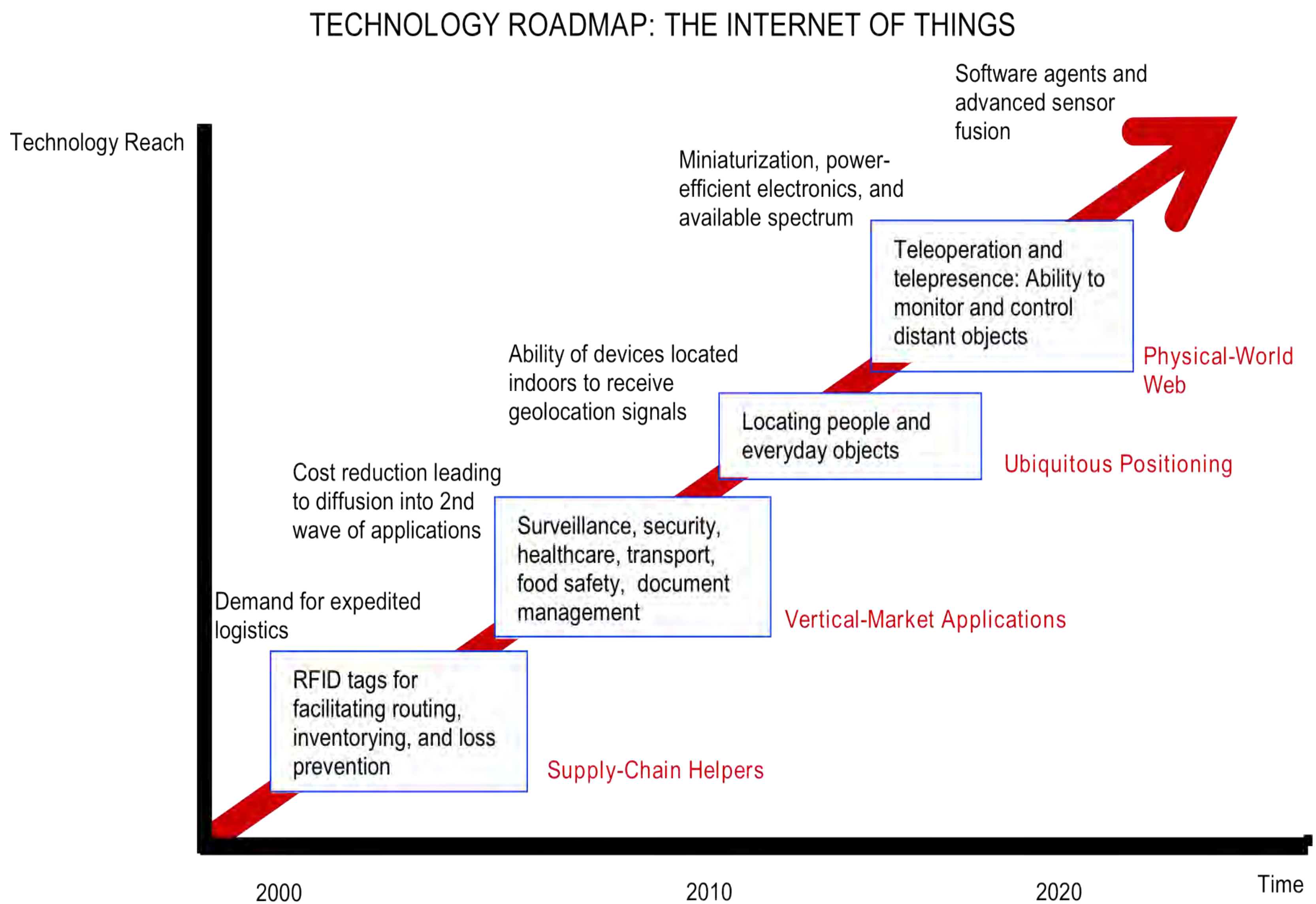
Quantity: 1 ▼

$349.00

Availability: Usually ships in 24 hours

Add To Cart

- FLIR One for IPhone5
- LWIR camera integrated in a light weight, battery-operated module.
- Available for $350 at www.FLIRone.com
- Mid-infrared is taking a leap into the mass market.



Source: SRI Consulting Business Intelligence

QCL Role in The Internet of Things?

- The “Internet of Things” will integrate sensor networks thus providing unprecedented functionalities in terms of real time, adaptive monitoring and data processing in the areas of sensing, imaging and many others.
- Mid-infrared photonics based on quantum cascade lasers (QCLs) is poised to make a major impact in these areas. Mid-IR QCL systems are achieving price performance levels that are increasingly attractive for an unprecedented broad range of sensing and testing applications
- This will require the development of small foot print, portable, efficient, high brightness QCL devices and subsystems without moving parts and of mid-IR integrated photonics (on-chip QCLs & components); mid-IR fiber coupled QCLs.

Why Mid-ir QCLs?

- The mid-IR region is most known for two large applications that make up much of their usage, infrared countermeasures (IRCM) on aircraft that distract missiles from hitting their real targets, the heat-source of the aircraft, and spectroscopy, a technology that is used to identify the signatures of certain materials or gases.
- Thermal imaging (illumination)
- **Identifying Chemicals and Substances**

  new sensor technologies for industrial, environmental, biomedical, and security sensing.
- Low cost medical care and homeland security are two very big topics in recent years, and also two areas that mid-IR lasers can provide significant benefits.
- Eye safety

QCL lasers are the fastest growing type of mid-IR laser, with a CAGR from 2012 to 2017 expected to exceed 30%. The driving force behind this is simple, IR countermeasures.

Source: Strategies unlimited

Sensors and spectroscopy: Drivers

- The fear of terrorist activity means that low-cost sensors are needed to detect explosives, and fears of global warming require better monitoring of environmental pollution and smokestacks. In healthcare, the drive for low-cost ways to better monitor and detect illness in patients is not only a need in developed countries but also in emerging ones

- All-in-all, designing a good sensor is a balancing act between sensitivity, selectivity, speed, price, size, reliability, and battery consumption.

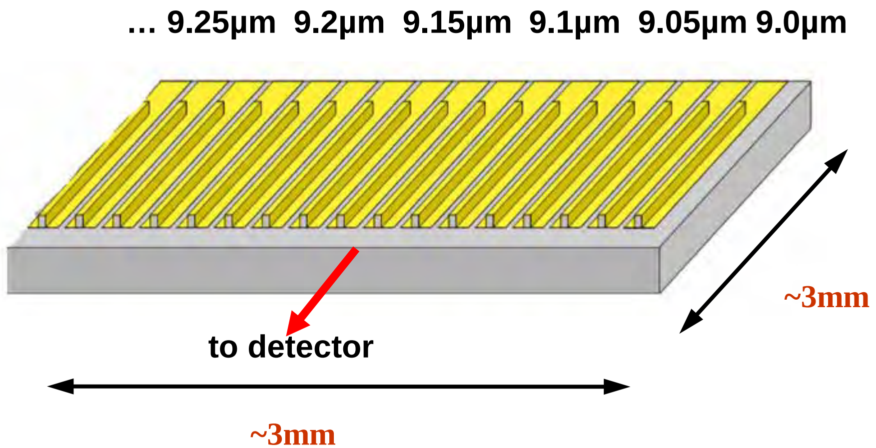
Source: Strategies unlimited

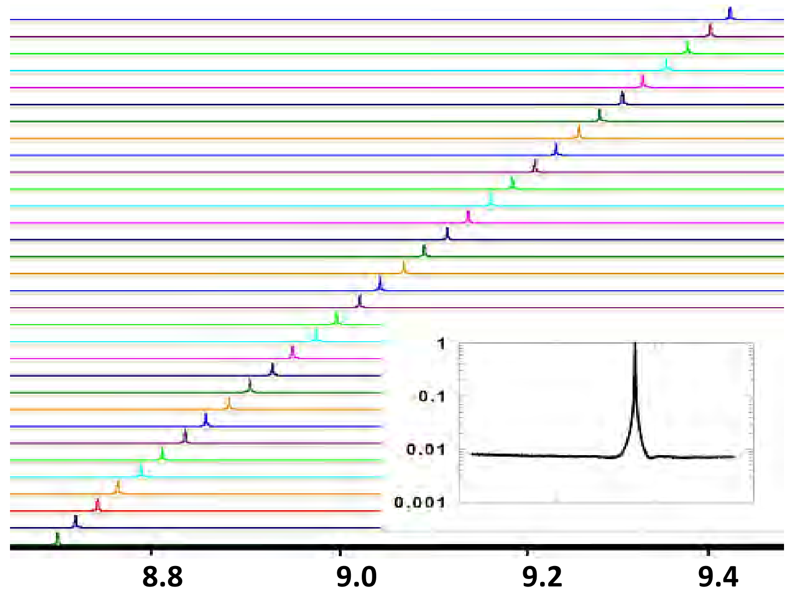
Table 1.2 Mid-IR Lasers Past and Future

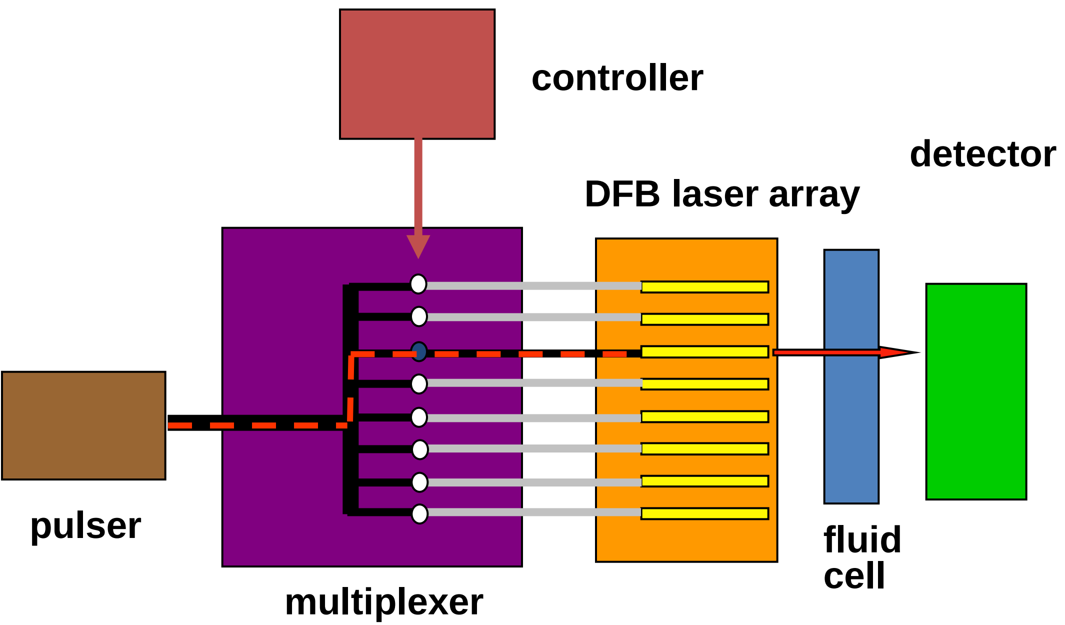
Time Period	Summary
1960s to 1980s: *R&D & Materials Processing Are Early Successes*	The industry first followed early opportunities for mid-IR lasers in R&D equipment, as most every laser technology has. From the R&D labs emerged other new laser applications. In the 1970s, CO_2 laser suppliers exploited a huge opportunity in materials processing. CO_2 lasers remain a key technology in that segment today, now shared with visible, UV, and near-infrared lasers.
1990s & 2000s: *Medical Applications Add Another Segment*	Applications for mid-IR medical lasers added a sizable segment in the 1990s, but competition with other laser and nonlaser solutions continues to limit their position there. Other than a few niche applications, the mid-IR laser market is still dominated by materials processing and medical applications, while new applications continue to be examined in labs using lasers in R&D equipment.
2010 - 2016: *Military and Spectroscopy Relaunch the Market*	The next decade will add military and spectroscopy to the market. The military is now using or testing high-brightness mid-IR sources for infrared countermeasures, illumination, and standoff detection. Key support for contract R&D and a few high-value (i.e., expensive) products helps drive new technology development forward for other applications, particularly for new spectroscopic methods that use the mid-IR for molecular detection.
2017+: *Low-Cost Applications in Healthcare & Sensing*	There are two obstacles to overcome in the mid-IR range that prevents wider adoption: high-cost and sometimes required cooling. As more room-temperature lower-cost mid-IR diode lasers hit the market, more applications will appear. Some of these areas include mobile healthcare (mHealth), in-office medical labs, mobile & remote sensing, low-cost industrial controls, and homeland security.

Source: Strategies Unlimited

Broadband Monolithic QCL-DFB Arrays





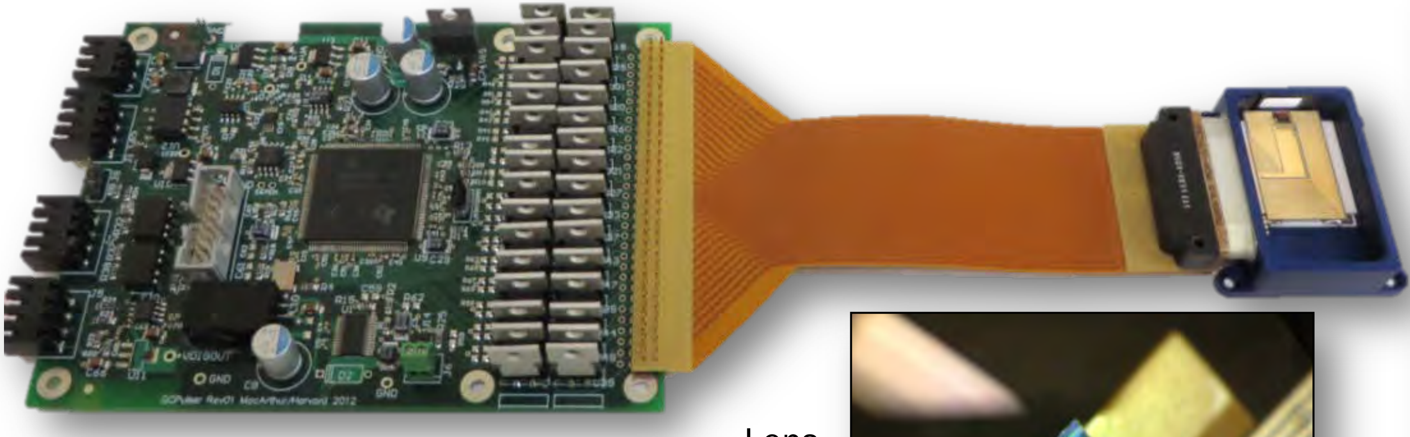


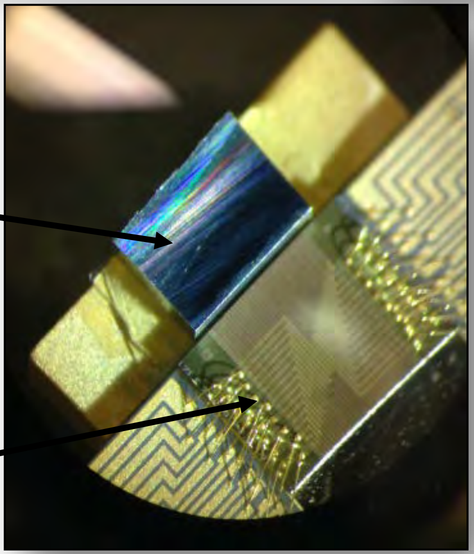
- ***Broadband mid-IR QCL material (8-10 μm)***
- ***Small-foot print***
- ***Rugged, portable and robust: no movable parts***
- ***Fast electronic tuning***
- ***Computer control***
- ***Core of "Matchbox" portable sensor***

EOS PHOTONICS

B. Lee, et al., APL 91, 231101 (2007)

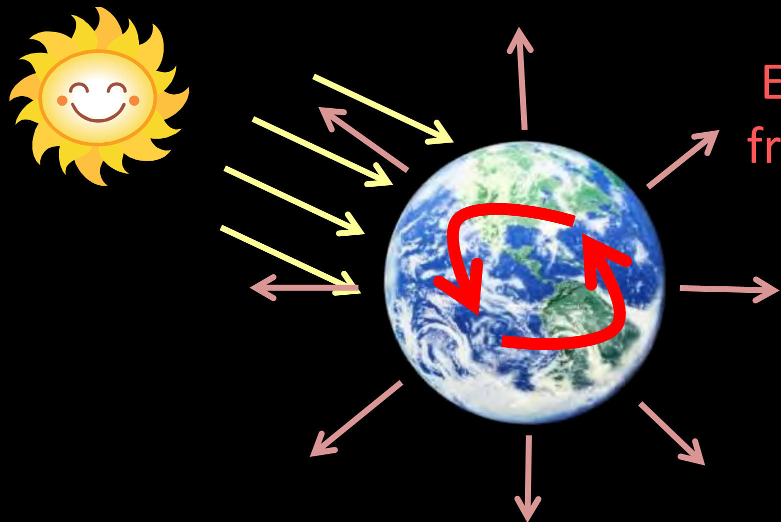
EOS Photonics Core Technology: The Matchbox (Prototype) Product





- Packaged 100, 150, 200 cm^{-1} arrays available in LWIR and MWIR
- Includes QCL pulser and software for sync. high speed laser control, DAQ, and signal processing
- Insertion into full sensor systems is ongoing
- Can be Incorporated in hand held device

Big picture of renewable energy



Entropy is generated as heat travels from hotter to colder areas on earth.

<u>Renewable energy:</u> Wind, hydroelectric, geothermal, waves, waste heat harvesting …

Entropy is generated when visible/NIR light energy is converted to lower-grade thermal energy.

<u>Renewable energy:</u> Solar photovoltaics, solar thermal, photosynthesis, biomass…

Entropy is generated when mid-IR radiation travels into 3K outer space.

<u>Renewable energy:</u> ???

…Emissive energy harvesters!

Harvesting renewable energy from Earth's mid-infrared emissions

Earth is continually emitting ≈ 10^{17} watts of IR radiation into outer space

≈ 200W/m^2 on average over the surface of Earth

(Not coincidentally, this is similar to incident sunlight energy, averaged over 24 hours).

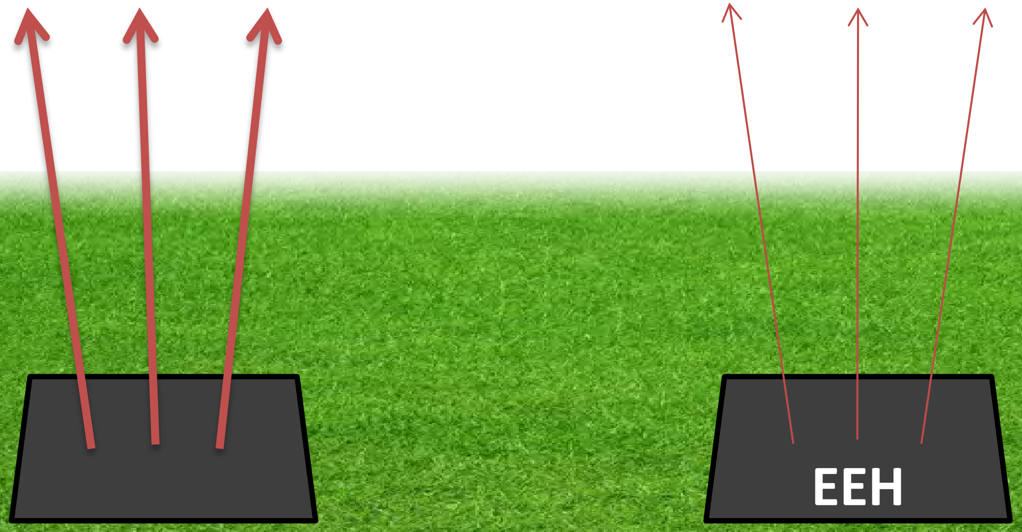
"Emissive Energy Harvester" (EEH) is something that <u>harvests energy</u> out of the process of <u>emitting</u> (net) thermal radiation.

S. Byrnes, R. Blanchard, F. Capasso, "Harvesting renewable energy from Earth's mid-infrared emissions" *PNAS* **111**, 3927 (2014)

Conservation of energy

Normal blackbody panel emits power *P*

EEH panel emits *less* power. The *difference* becomes DC electricity



Concept

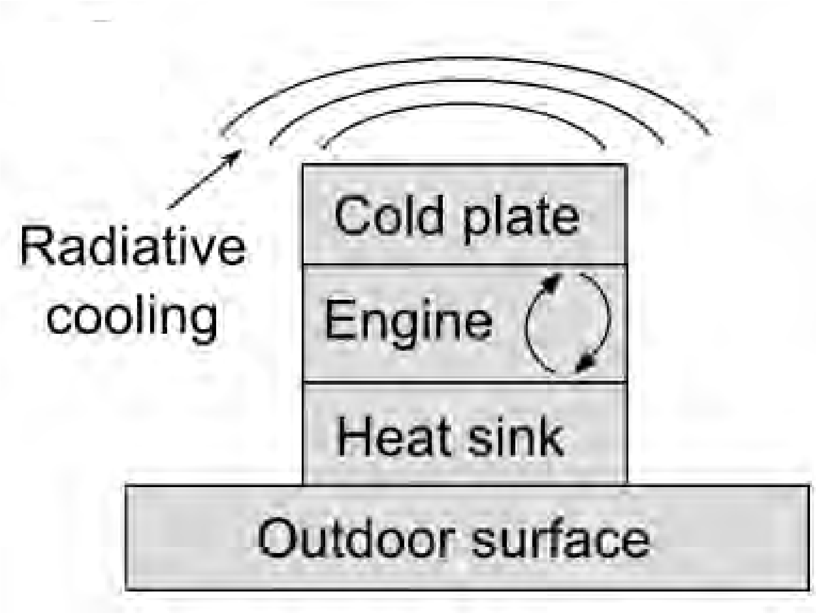
- **We propose a device that has a large emissivity in the long-wave infrared (LWIR) "atmospheric window" at 8–13 μm, where the atmosphere is mostly transparent, and small emissivity at other wavelengths, where the atmosphere is mostly opaque.** It would sit outdoors with its emissive surface pointing upward, emitting thermal radiation toward the sky, but receiving far less radiation back. This imbalance between incoming and outgoing radiation can be converted into useful electrical power.

- With a perfectly transparent atmosphere, an EEH would be a kind of heat engine harnessing the temperature difference between Earth's surface at ∼275–300 K and outer space at 3 K.

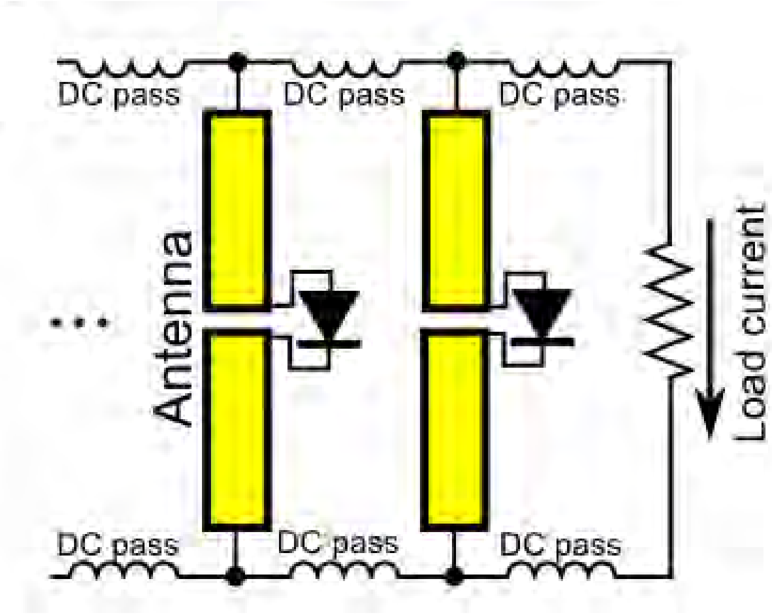
- In reality EEH power generation will be affected by weather and atmospheric conditions—and stopped altogether by thick, low clouds. **On the other hand, because the Sun emits negligible LWIR compared with the atmosphere, an EEH can operate during both day and night.**

Two approaches

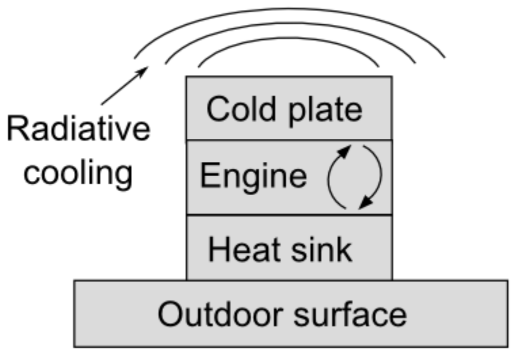
“Thermal EEH”



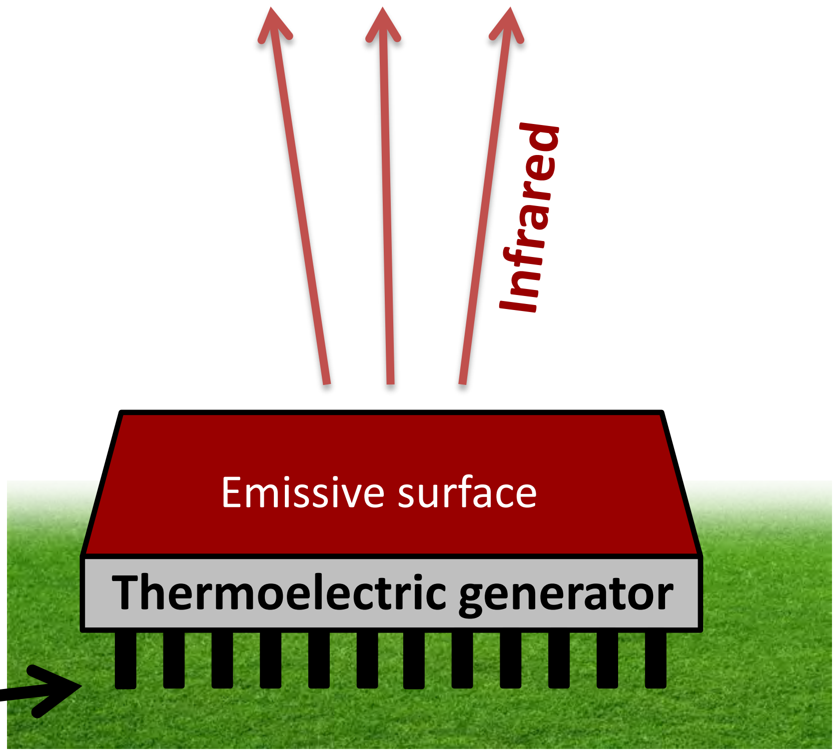
“Optoelectronic EEH”



Simple example of thermal EEH



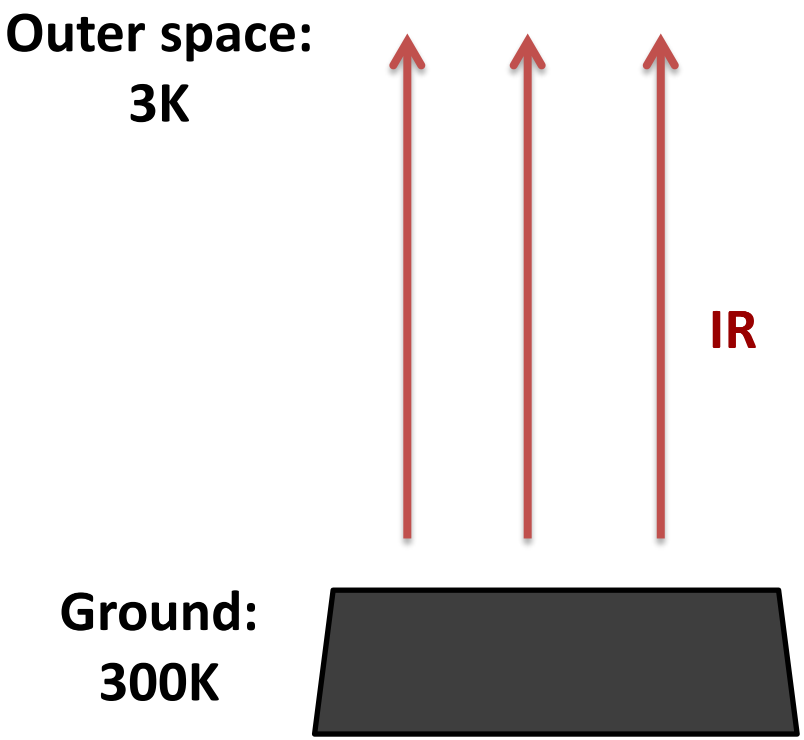
Radiative cooling keeps the top side **below** ambient temperature



Heat sink keeps the bottom side **at** ambient temperature

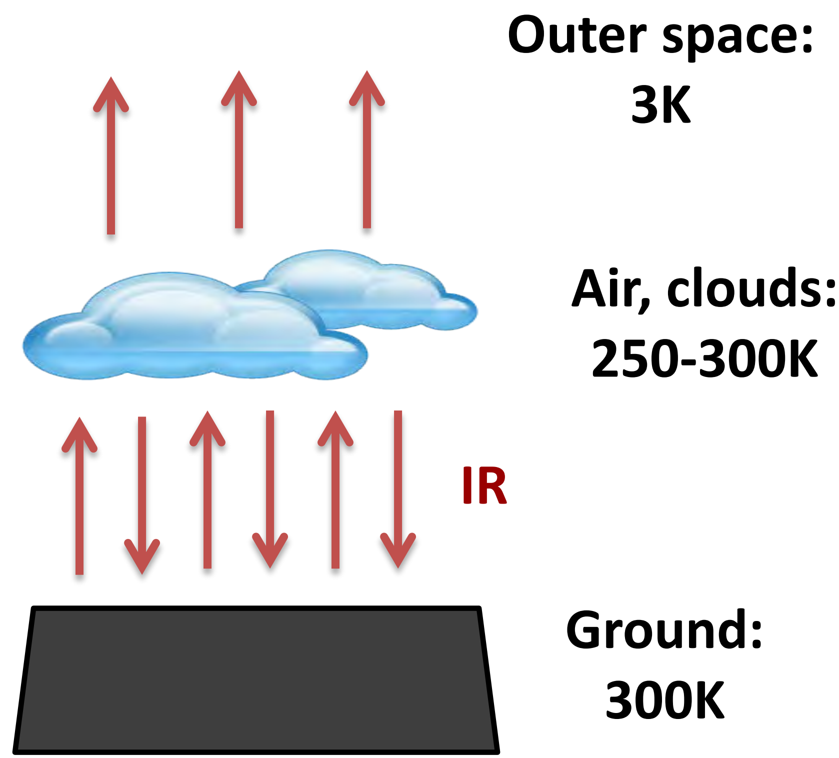
A transparent sky is important

Ideal



A device on the ground sees a large temperature difference

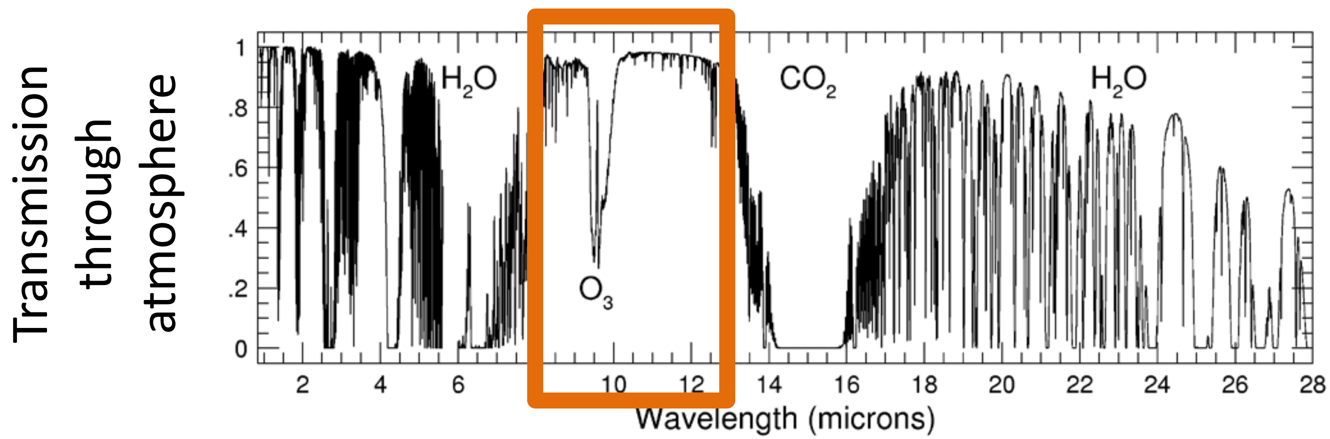
Real



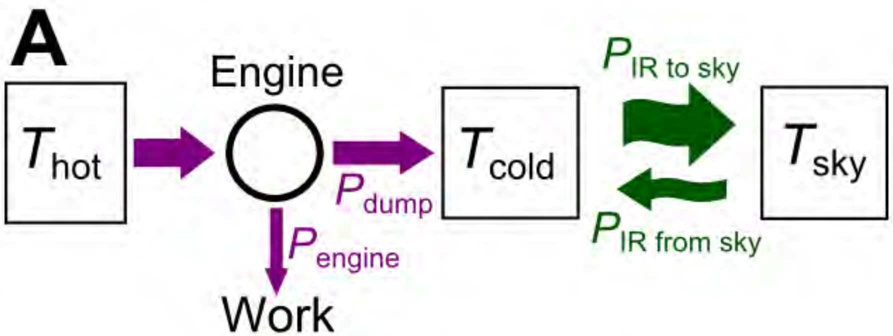
A device on the ground sees a small temperature difference

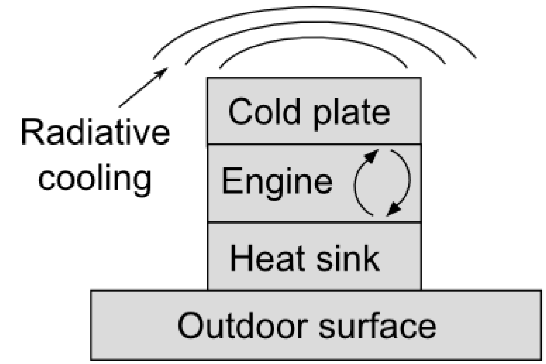
A transparent sky is important

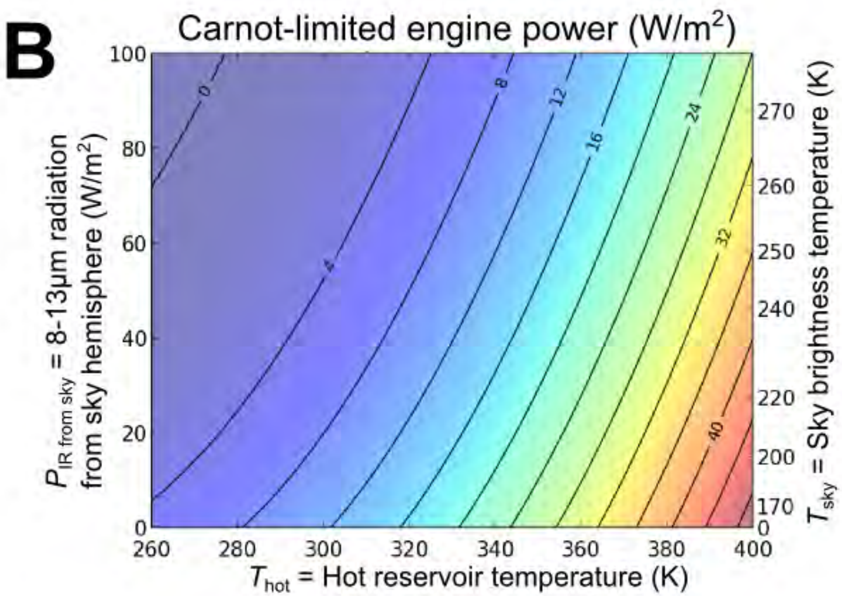
- The device is designed to be sensitive only in the 8-13μm "atmospheric window", where the atmosphere is *mostly* transparent (without clouds).
- Conveniently, objects on earth radiate a significant amount of thermal radiation in the 8-13μm range.
  - At 280-500K, 30-35% of blackbody radiation is at 8-13μm



Carnot-limit power







Calculation method:

$$P_{\text{dump}} = P_{\text{IR to sky}} - P_{\text{IR from sky}}$$

$$P_{\text{engine}} \le P_{\text{dump}} \Big((T_{\text{hot}} / T_{\text{cold}}) - 1 \Big)$$

Putting these together:

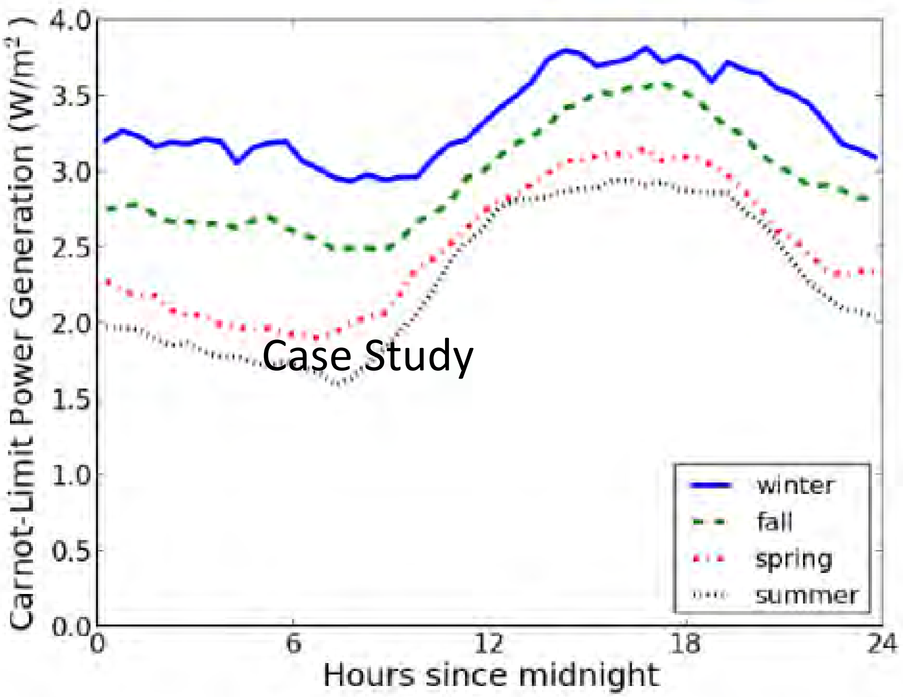
$$P_{\text{engine max}}(T_{\text{hot}}, T_{\text{sky}}) = \max_{T_{\text{cold}}} \left[\left(\frac{T_{\text{hot}}}{T_{\text{cold}}} - 1 \right) \left(f(T_{\text{cold}}) - f(T_{\text{sky}}) \right) \right]$$

$$f(T) = \int_{8\mu\text{m}}^{13\mu\text{m}} \frac{2\pi h c^2}{\lambda^5} \frac{1}{e^{hc/\lambda k_B T} - 1} d\lambda$$

Carnot-limit power

- Power can be generated during both day and night.
  - …Unless there are thick, low clouds.
- Available power depends on weather and climate.
- Case study: We can calculate this Carnot limit for a particular location.
  - There is a facility in Lamont, Oklahoma, USA which measures downwelling infrared intensity.

Carnot-limit power

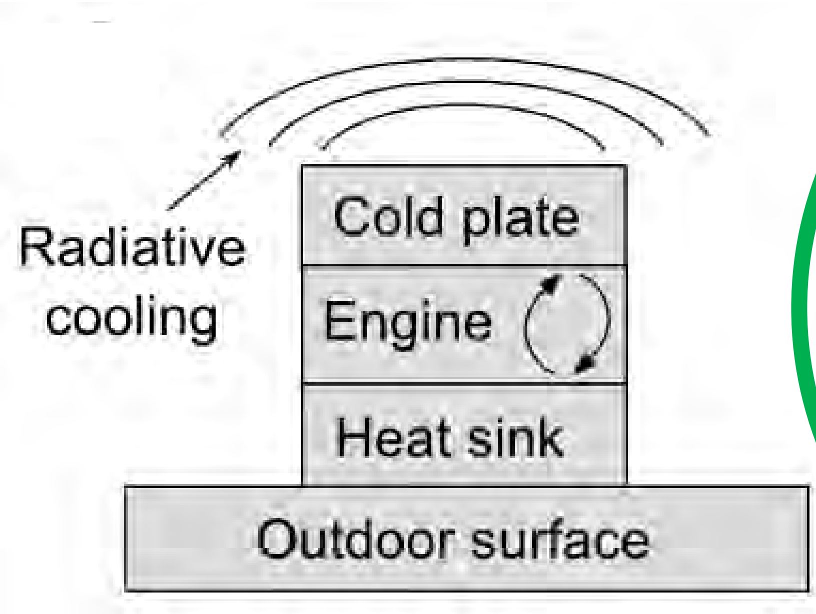


Comparable to a 1.5% efficient solar cell in this location (if you average across 24 hours).

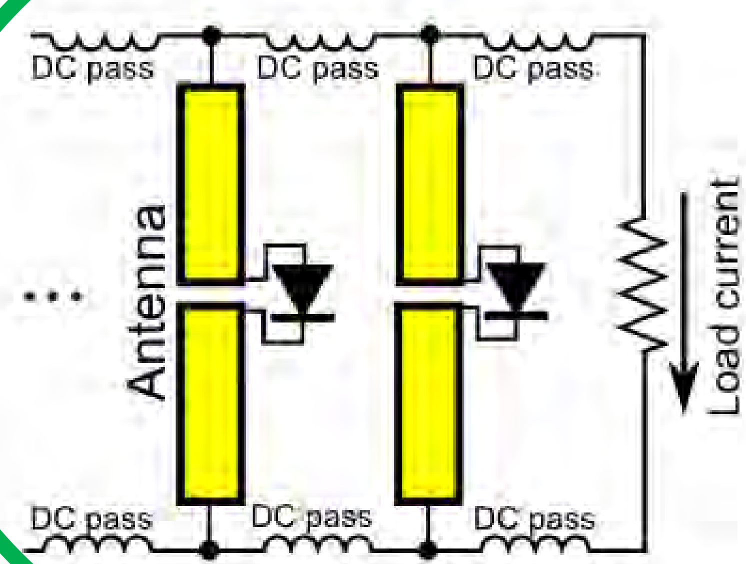
(Maybe 5× more power with solar heating)

How does an optoelectronic EEH work?

"Thermal EEH"



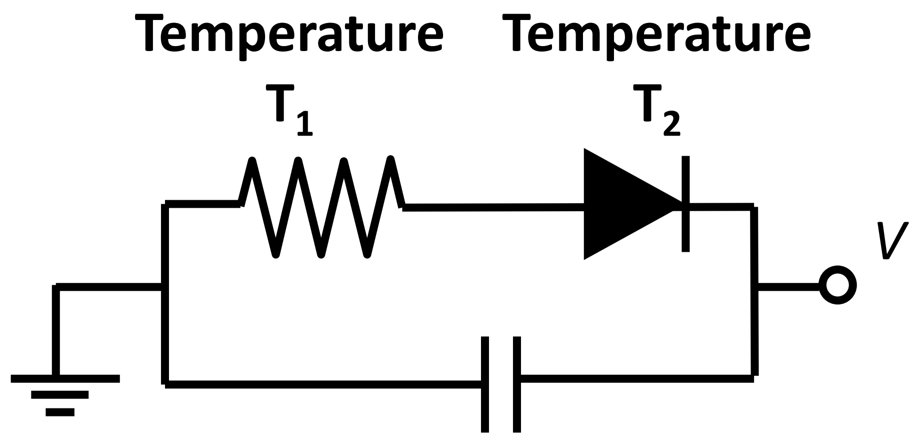
"Optoelectronic EEH"



Rectifying Antenna (“Rectenna”) EEH

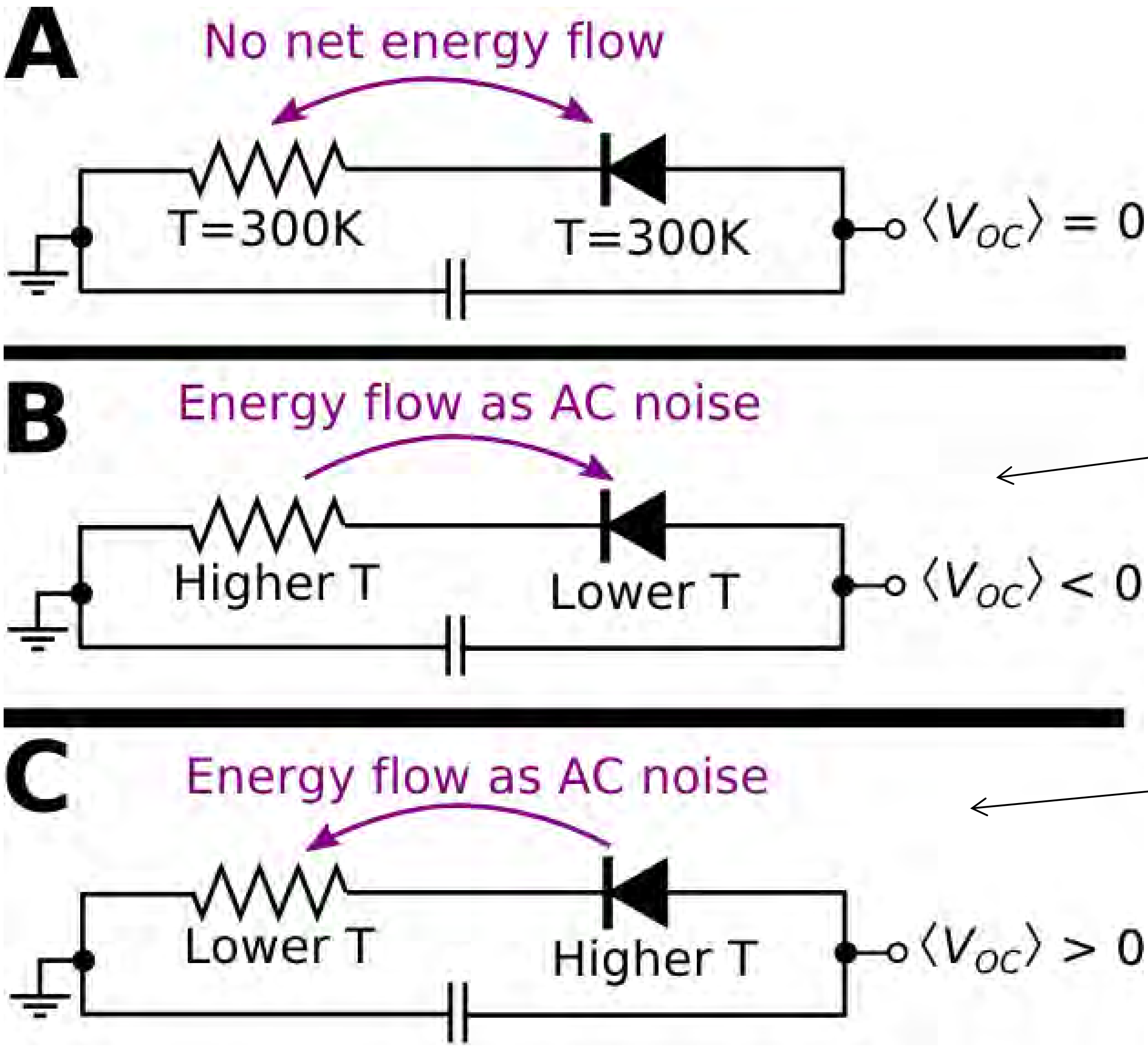
- How does a rectenna work?
  - Microwave engineers will answer: “A strong radiation field creates an AC voltage across the antenna, which the diode rectifies to DC.”
- That answer is specific to the regime where the diode's thermal fluctuations are irrelevant.
- We need a different description:
  - “A rectenna is a variant of the *diode-resistor generator circuit*.”

Diode-resistor generator circuit



- Physicists have studied this circuit from time to time
  - Toy model for nonequilibrium thermodynamics
  - Theory and experiments by JB Gunn in 1968
  - Microscopic model by IM Sokolov in 1998
- Conclusion: The circuit generates DC electric power when $T_1 \neq T_2$

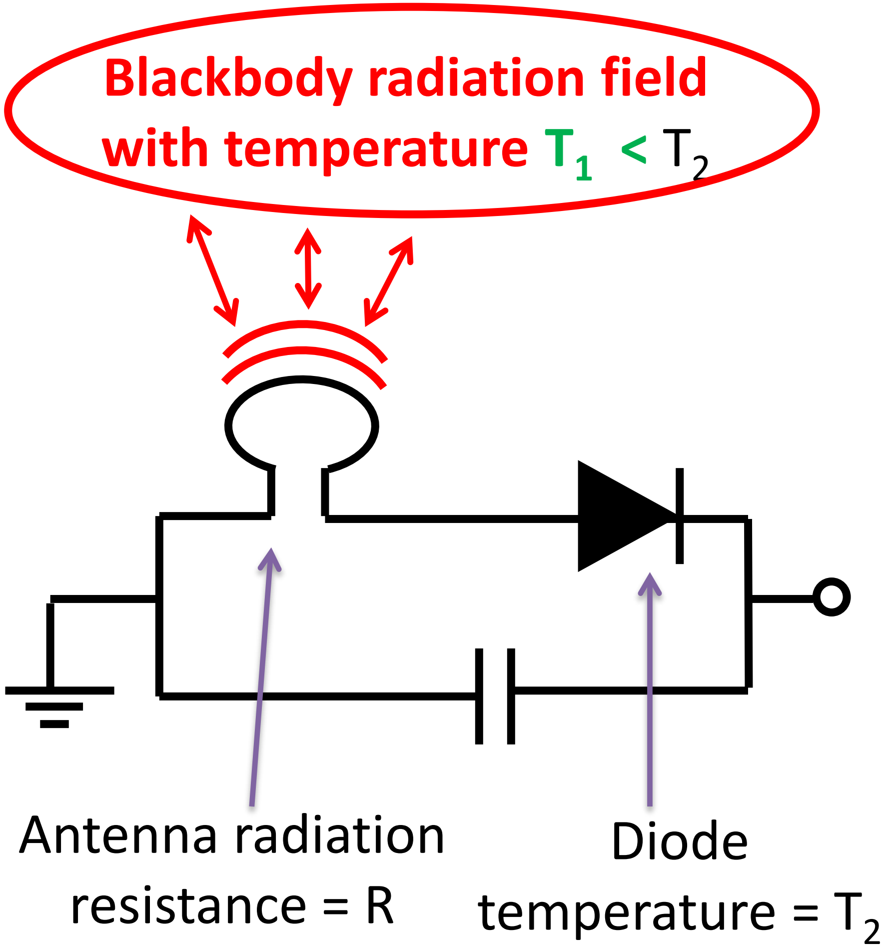
Diode-resistor generator circuit

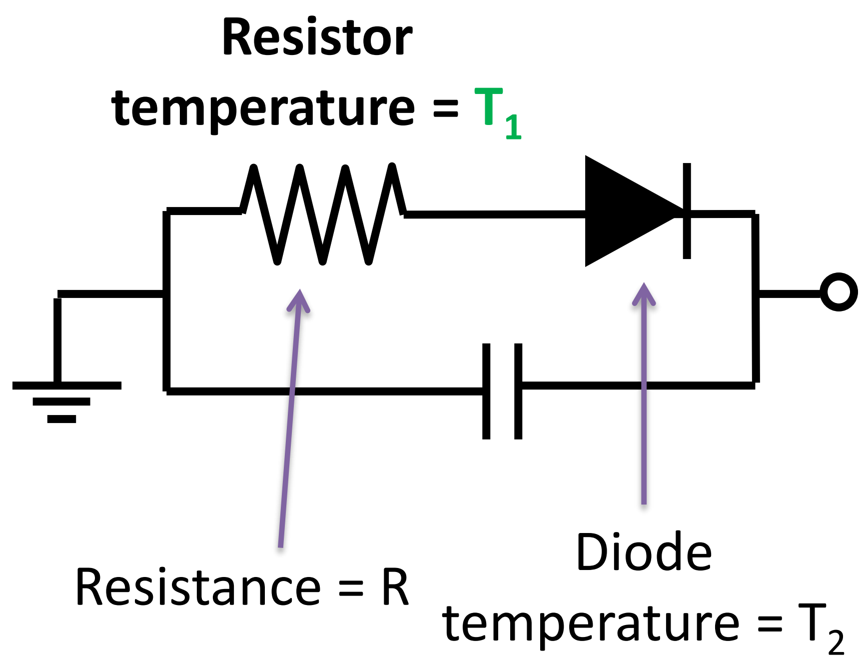


Ordinary use of a rectenna

Rectenna in "EEH mode"

Rectenna *versus* Diode-resistor generator circuit





These two circuits are electrically identical.

Equivalence between an antenna and a resistor

- As long as its radiation efficiency is high, an antenna **electrical noise temperature equals the brightness temperature of the incoming radiation field** .

- In other words, **an antenna in a strong radiation field imitates a hot resistor**, and **an antenna in a weak radiation field imitates a cold resistor,** regardless of the temperature of the antenna itself.

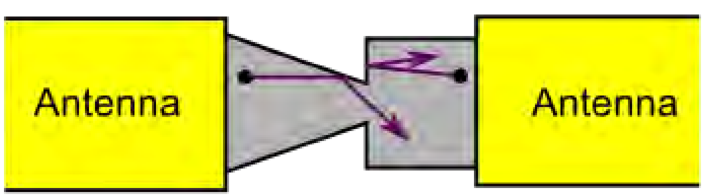
- This is a consequence of **the fluctuation-dissipation theorem (1)**: **A resistor dissipates electrical energy into phonons**, and **an antenna "dissipates" electrical energy into electromagnetic radiation**

(1) H. B. Callen and T. A. Welton, Irreversibility and Generalized Noise Phys. Rev. 83, 34 (1951)

Rectenna EEH: Practical challenges

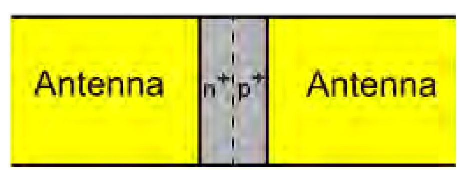
- Infrared-frequency antennas: Easy
  - Probably scalable with nanoimprint lithography
- Infrared-frequency diodes: Ongoing challenge
  - Must be fast enough for 30 THz
  - Must be highly asymmetric at very low voltage
  - However, there has been promising progress recently, with several different approaches

Ballistic (“Geometric”) diodes

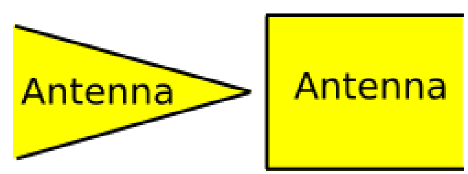


G. Moddel, Univ. Colorado

Backwards tunnel diodes



Nonplanar MIM diodes



B. Willis, Univ. Connecticut