Near-Zero Power Integrated Microsystems for the IoT

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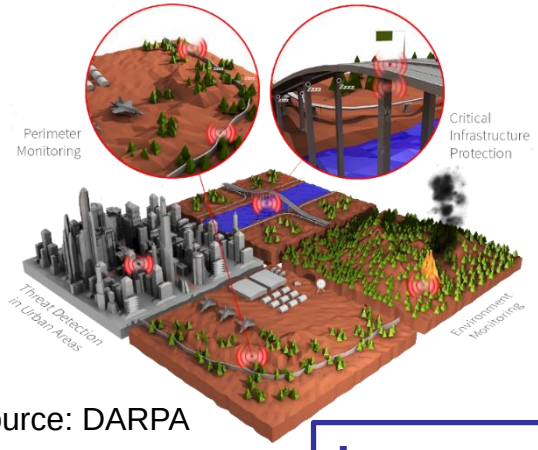
IoT Energy Challenge

- Internet of Things challenge: deployment and maintenance of 1000s wireless sensors
- Current deployment limited to 100s of nodes: **Energy is the key challenge!**
- **Battery replacement costs are unsustainable** for many sensors in challenging environments



Source: DARPA

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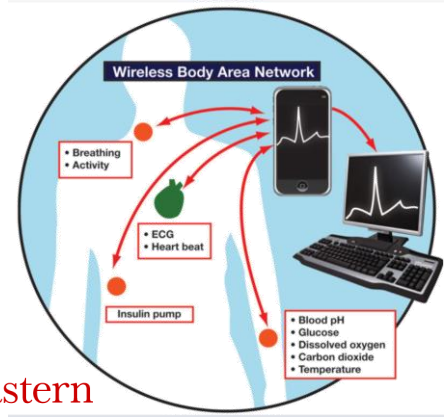
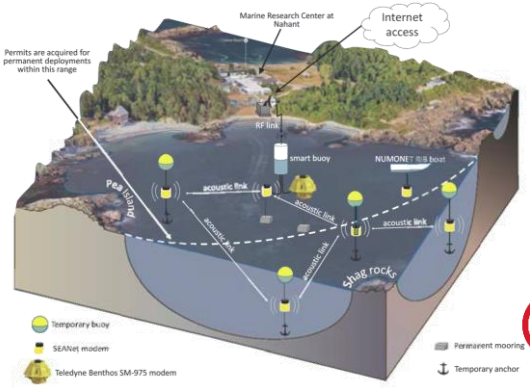
Increase the number of IoT sensors in challenging environments





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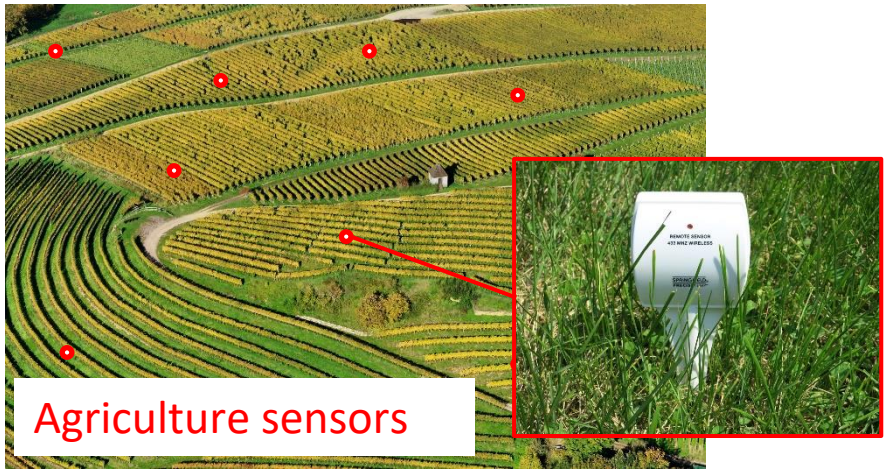
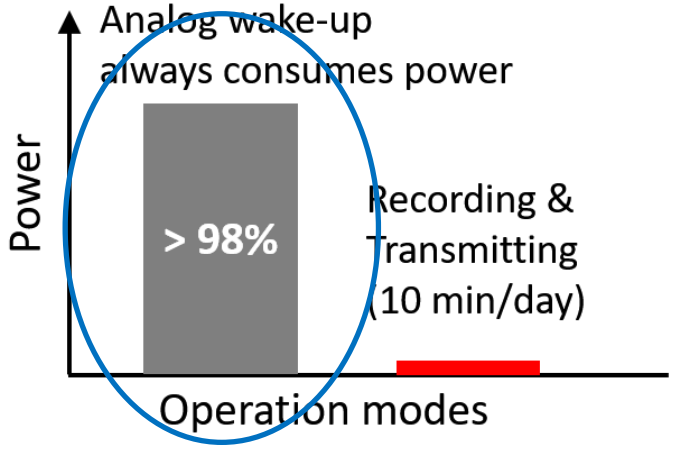
IoT Energy Challenge

Recharge battery frequently is not always possible

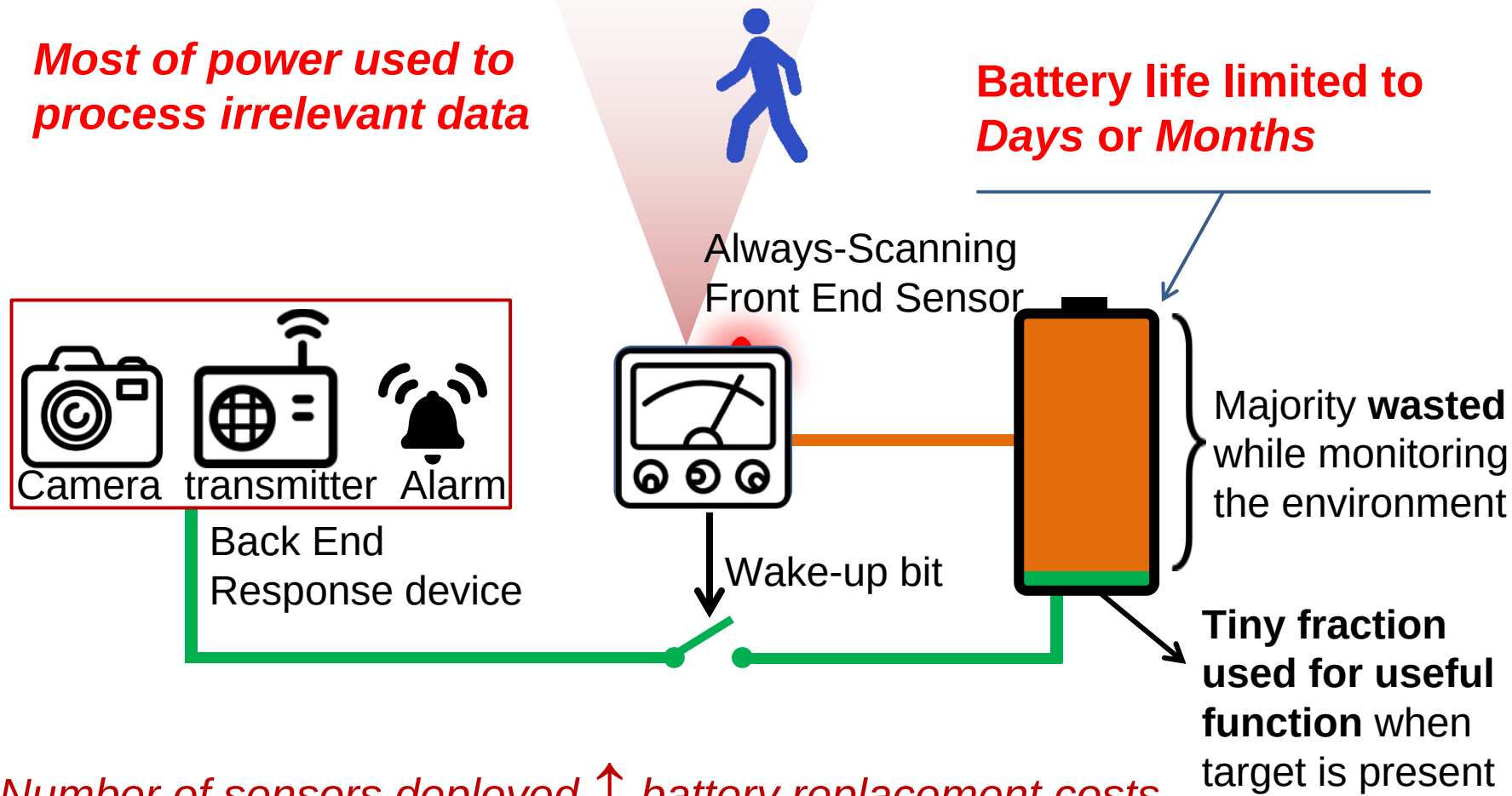


Power use in a typical UGS node:



Used for continuous sensing and signal processing

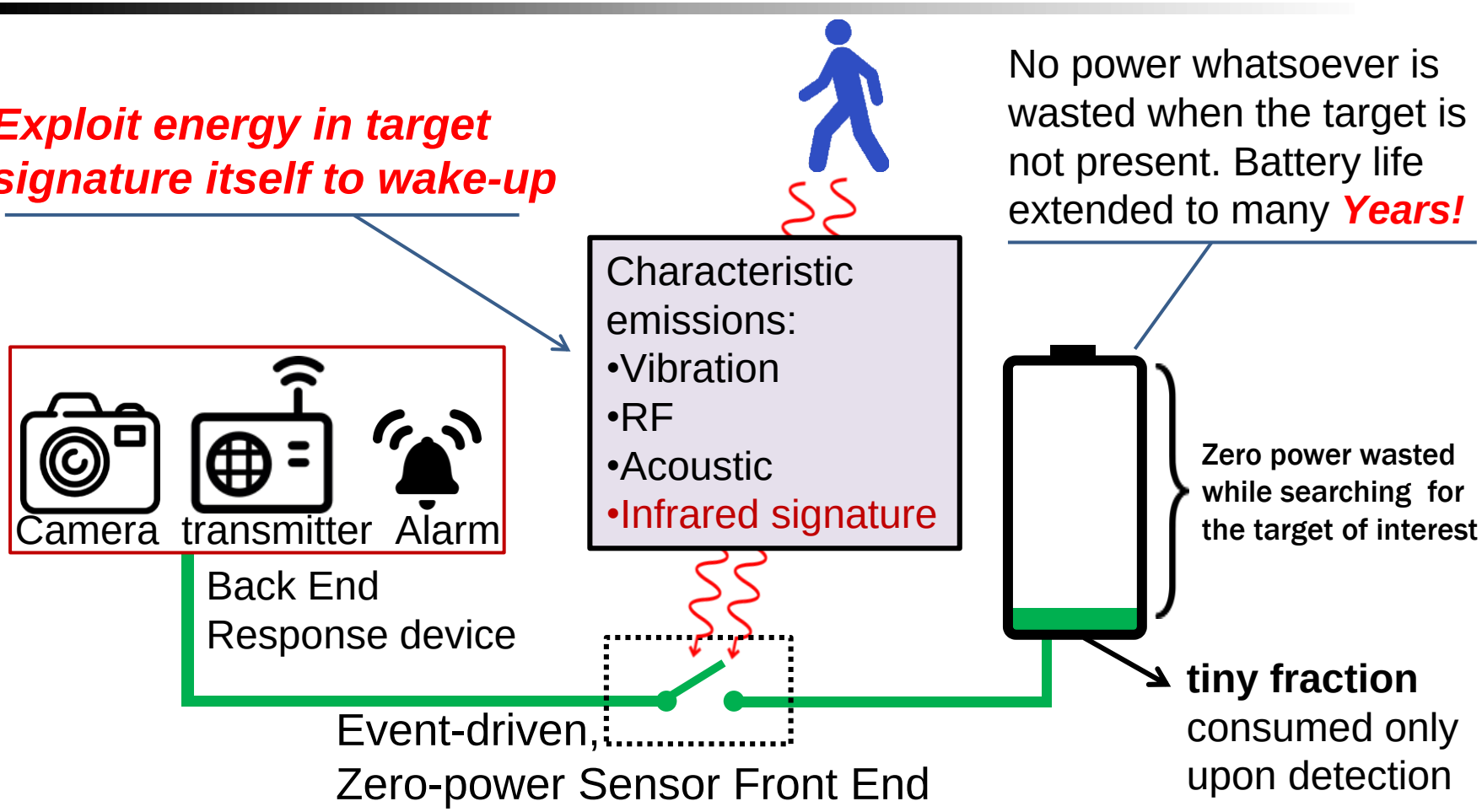
Energy Bottleneck in Environmental Sensors



↑*Number of sensors deployed* ↑ *battery replacement costs*

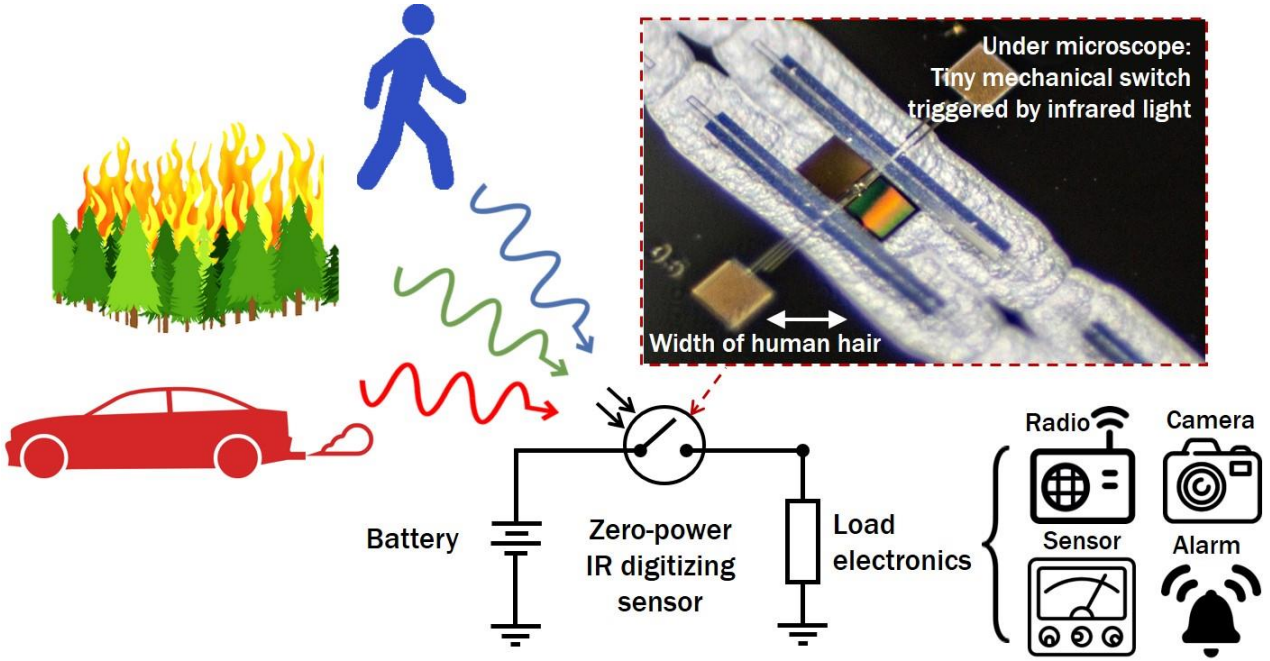
→ ***Severe bottleneck for internet-of-things (IoT) revolution!***

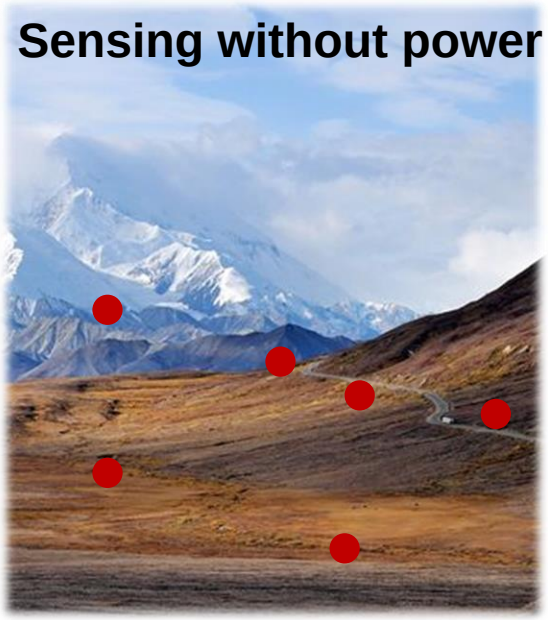
Solution: Event-Driven sensors



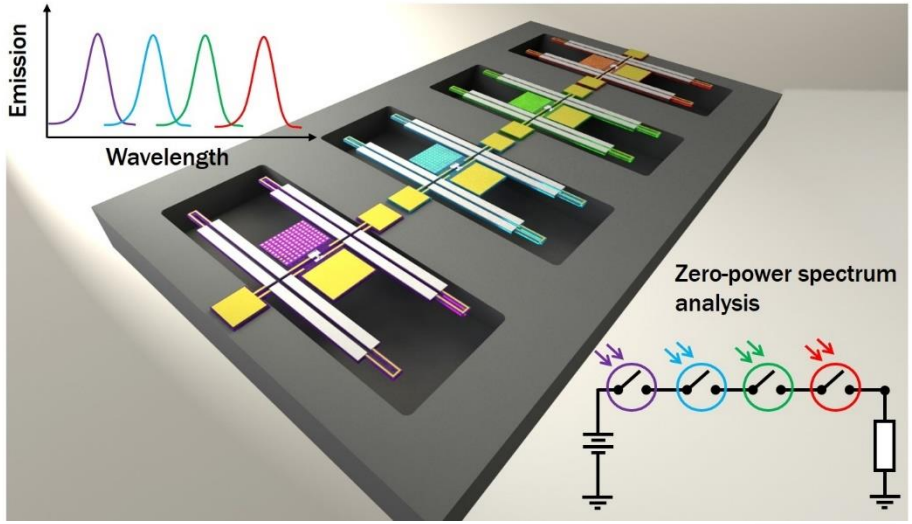
Break the paradigm *of using* ***active electronics*** *to detect targets!*
→ Enables new class of ASLEEP-but-ALERT systems *with near-unlimited battery life.*

Zero-Power Infrared Digitizing Sensors



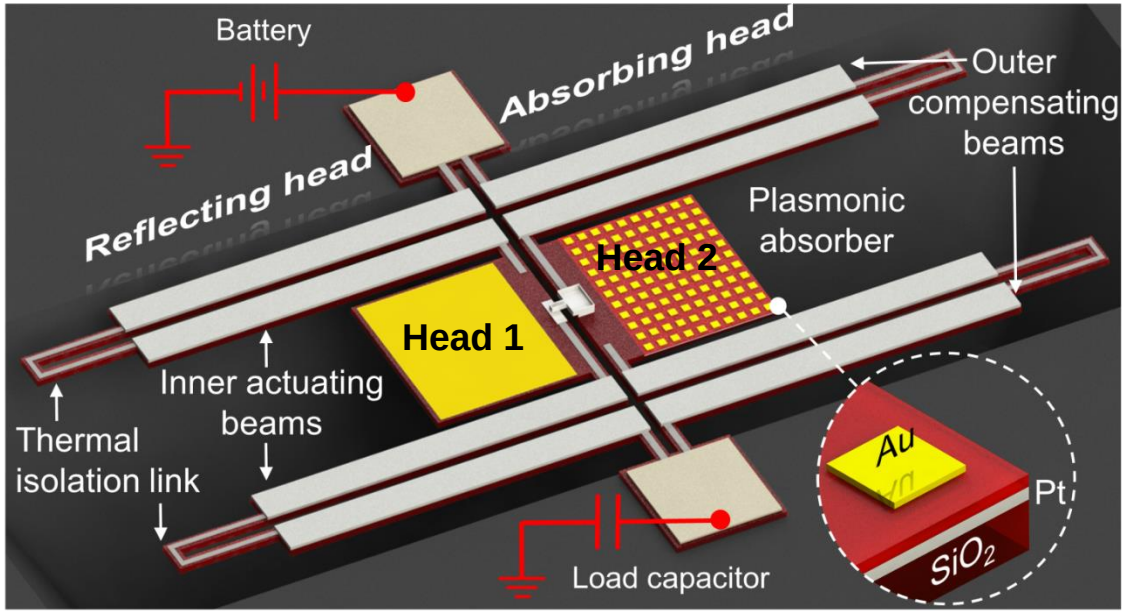


- A **passive microsystem** that combines **sensing**, **signal processing** and **comparator** functionalities.
- The sensor produces **a digitized output bit** in the presence of the unique **IR spectral signatures**.

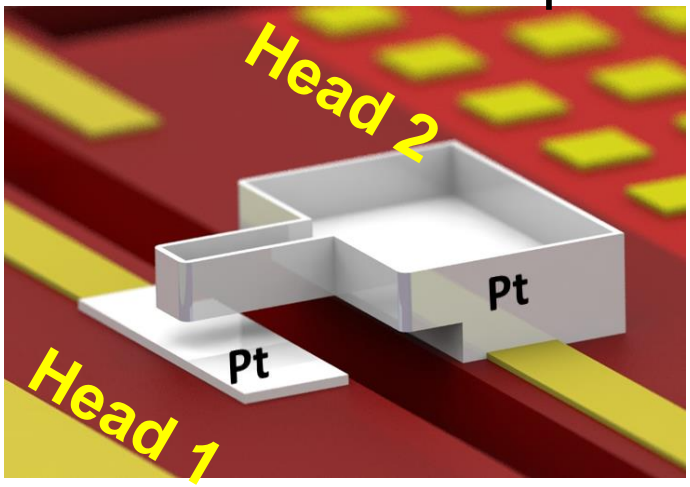


Plasmonic Microelectromechanical Infrared Digitizer

- *Plasmonically-enhanced MEMS relay (PMR)*



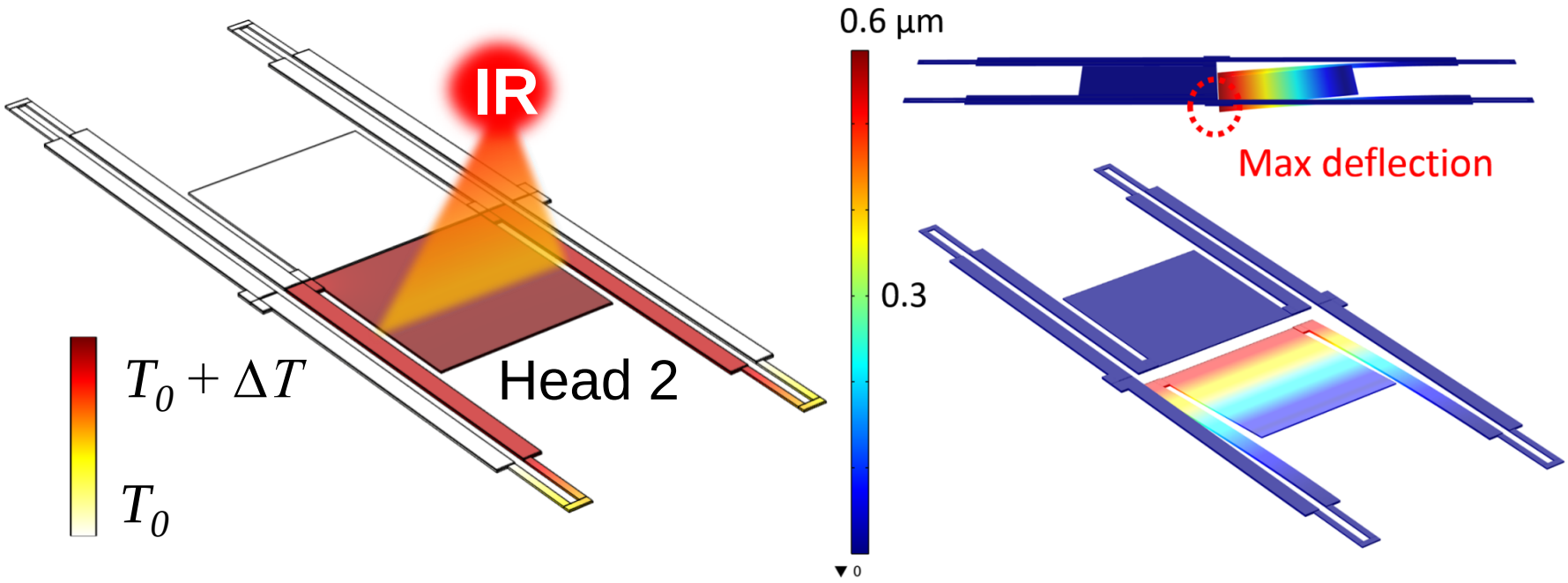
Contact Close-up



Z. Qian, S. Kang, V. Rajaram, C. Cassella, N. E. McGruer, and M. Rinaldi, *"Zero Power Infrared Digitizers Based on Plasmonically-enhanced Micromechanical Photoswitches"*, **Nature Nanotechnology**, vol. 12, issue 10, pp. 969 – 973, 2017. doi:10.1038/nnano.2017.147

Plasmonic Microelectromechanical Infrared Digitizer

- The gap separating the PMR contacts is directly controlled by the impinging IR radiation through a **plasmonically-enhanced thermomechanical coupling**



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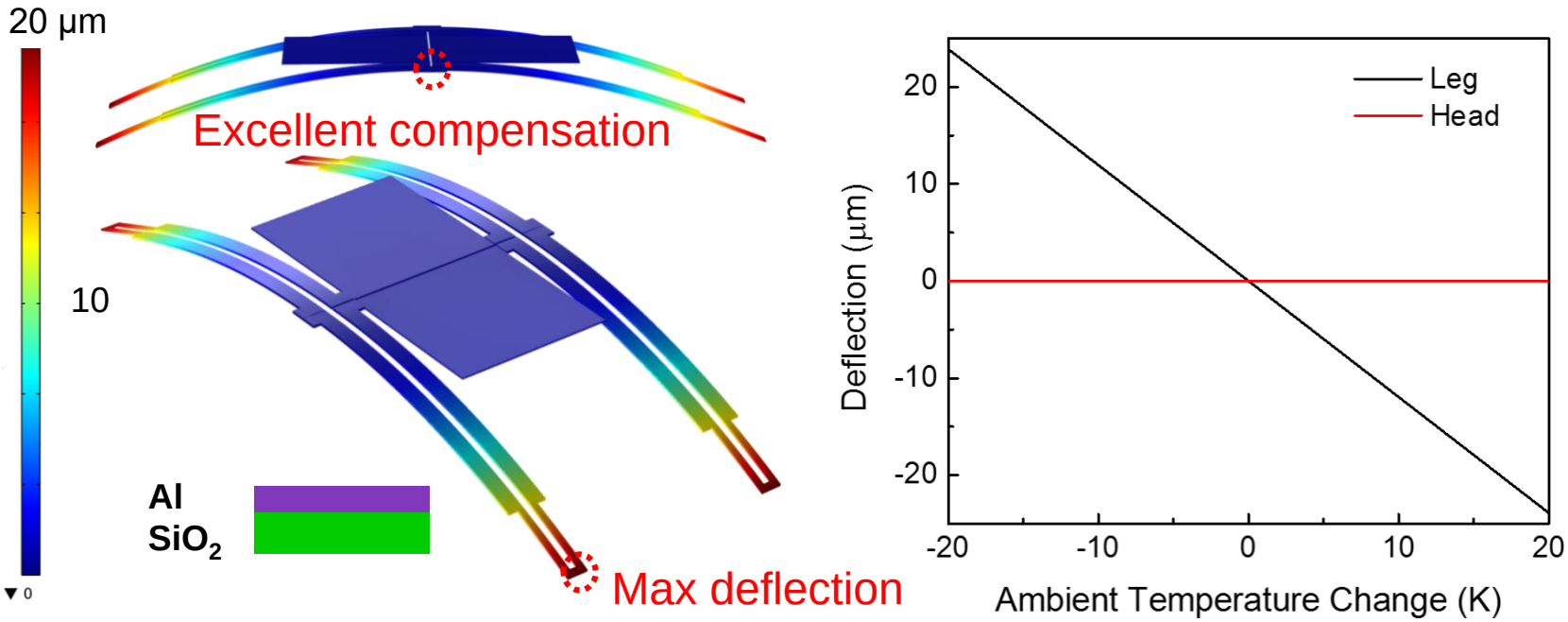
Plasmonic Microelectromechanical Infrared Digitizer

- **PMR is immune to ambient temperature changes and residual stress**



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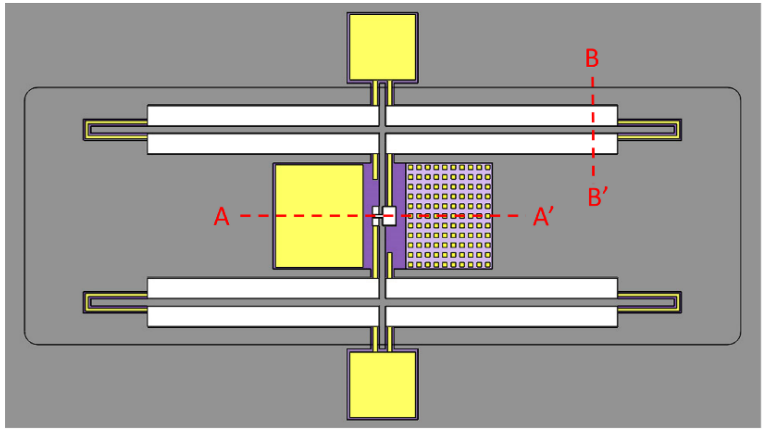
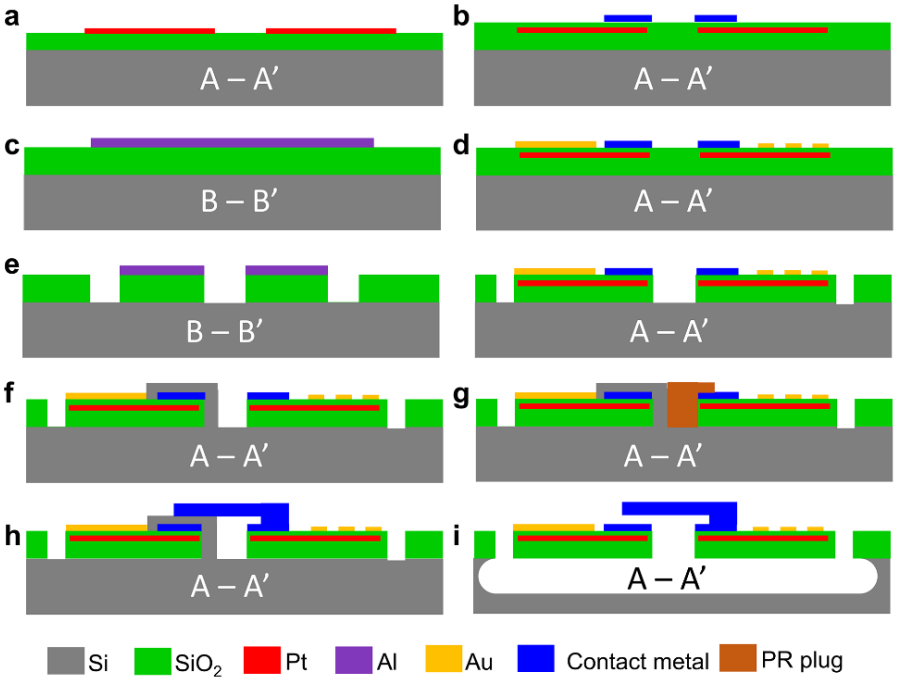
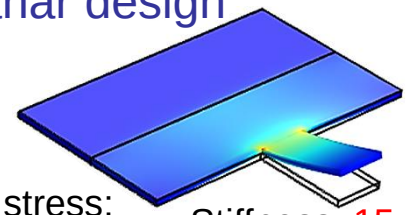
Plasmonic Microelectromechanical Infrared Digitizer





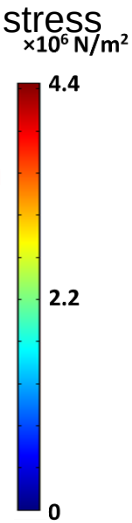
A key factor for success: Robust Contacts

Planar design

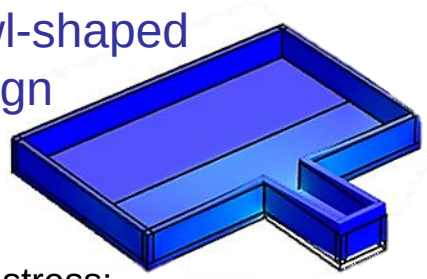


Max stress: 4.36×10^6 N/m^2

Stiffness: 15 N/m



Bowl-shaped design



Max stress: 1.82×10^6 N/m^2

Stiffness: 43.1 N/m

~3x better stress handling and stiffness

→ >95% yield

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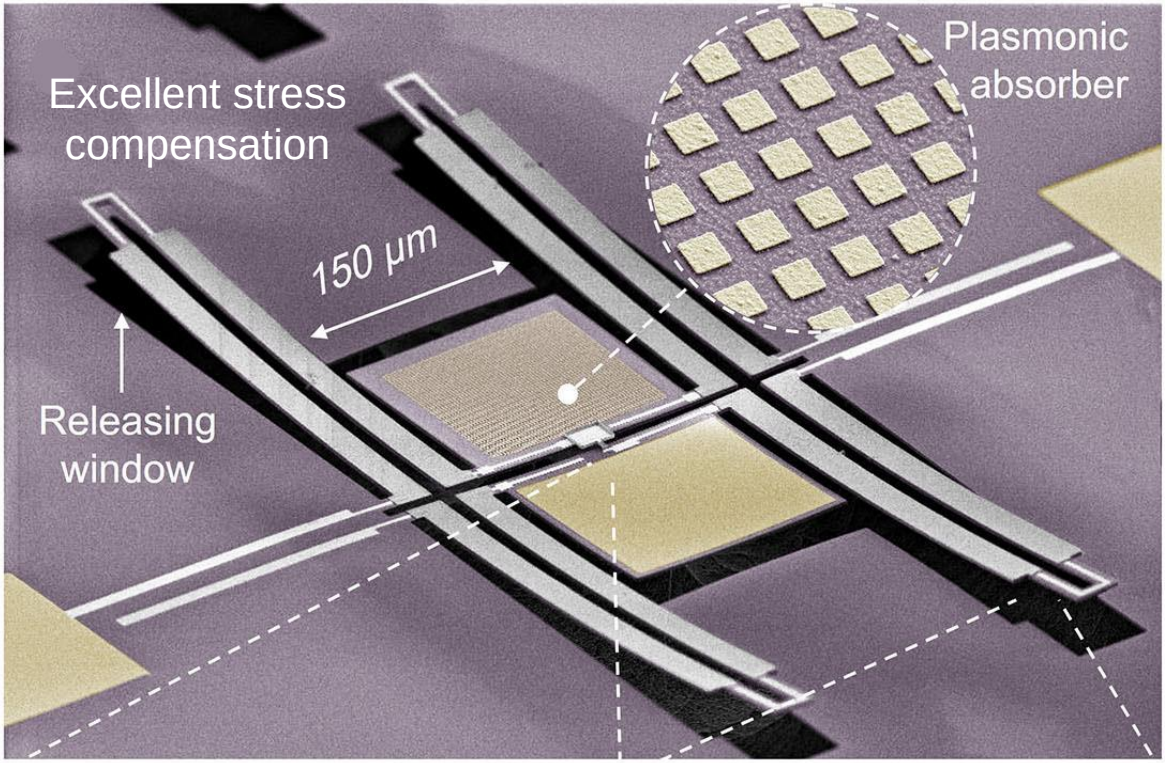
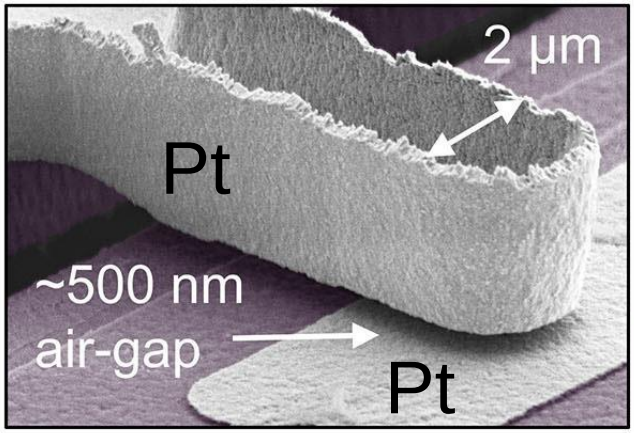
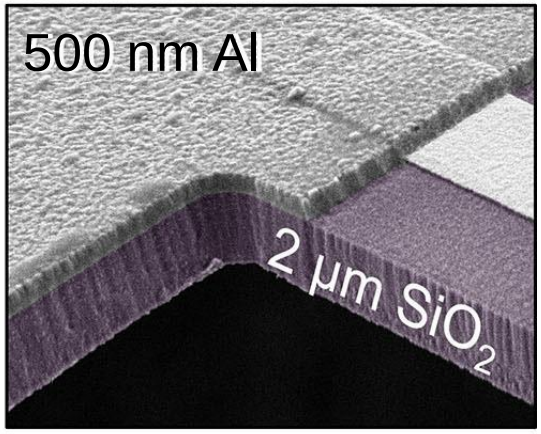
Plasmonic Microelectromechanical Infrared Digitizer







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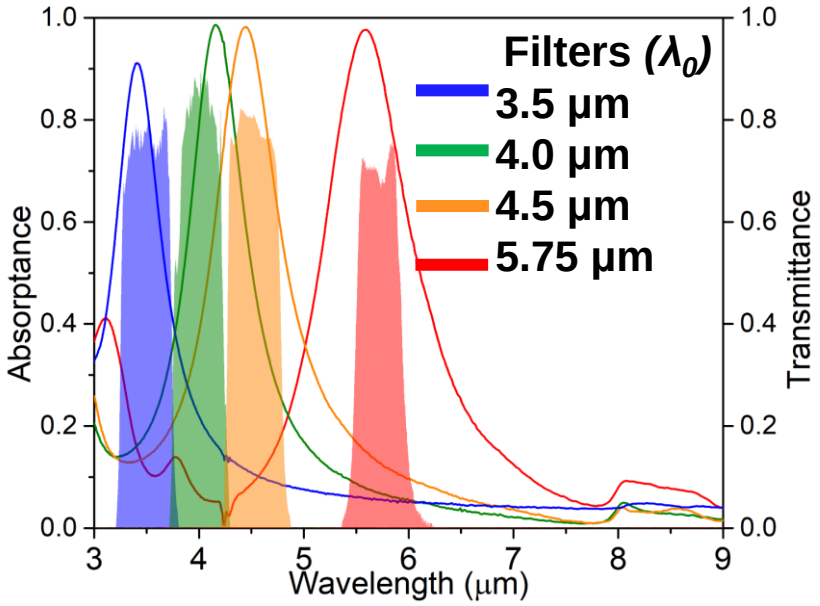
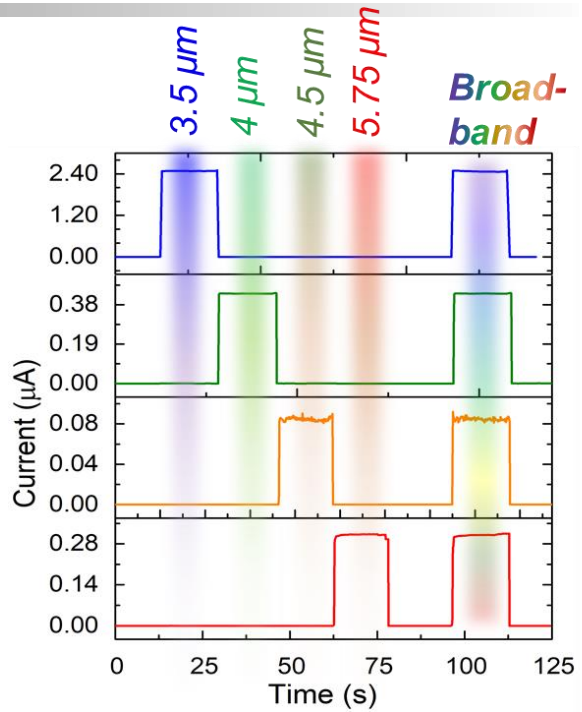
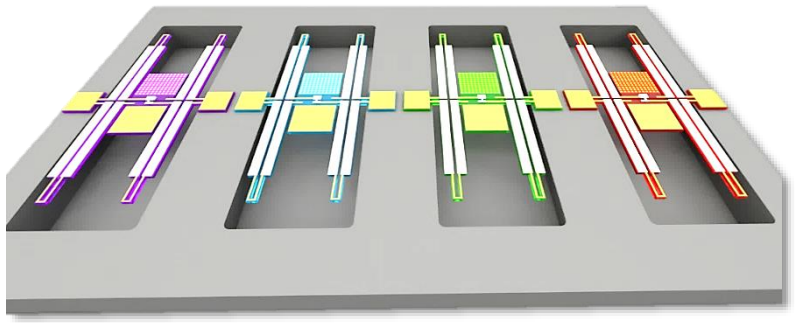
4 bit Zero-Power IR Digitizer

Device	Infrared Spectral State				
	3.5μm Band	4.0μm Band	4.5μm Band	5.75μm Band	Broad-band
3.4μm PMP	1	0	0	0	1
4.1μm PMP	0	1	0	0	1
4.5μm PMP	0	0	1	0	1
5.6μm PMP	0	0	0	1	1







V. Rajaram, Z. Qian, S. Kang, C. Cassella, N. McGruer and M. Rinaldi, "Microelectromechanical Detector of Infrared Spectral Signatures with Near-Zero Standby Power Consumption", Proceedings of the 19th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers 2017), Kaohsiung, Taiwan, June 18-22, 2017, pp. 846-849

Zero Standby Power Consumption

Average noise amplitude: ~ 5 fA

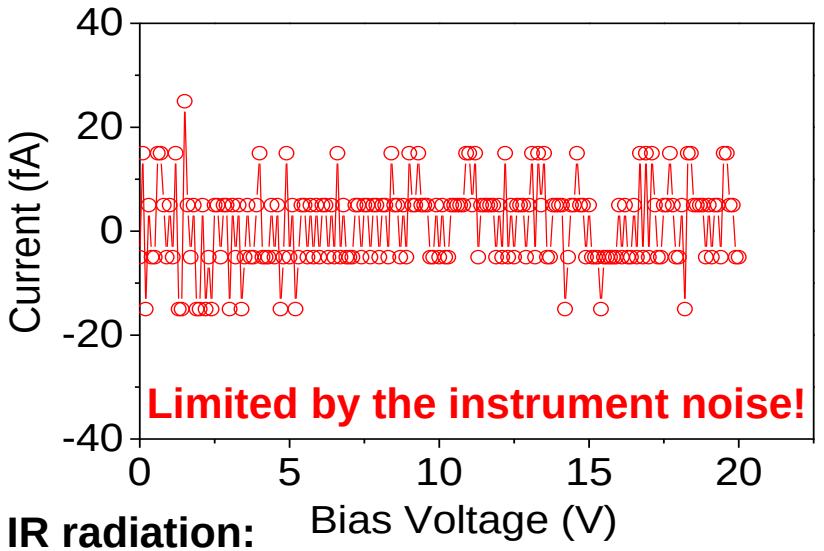
OFF-state resistance > 4×10^{15} Ω

Standby power consumption **< 1 fW**

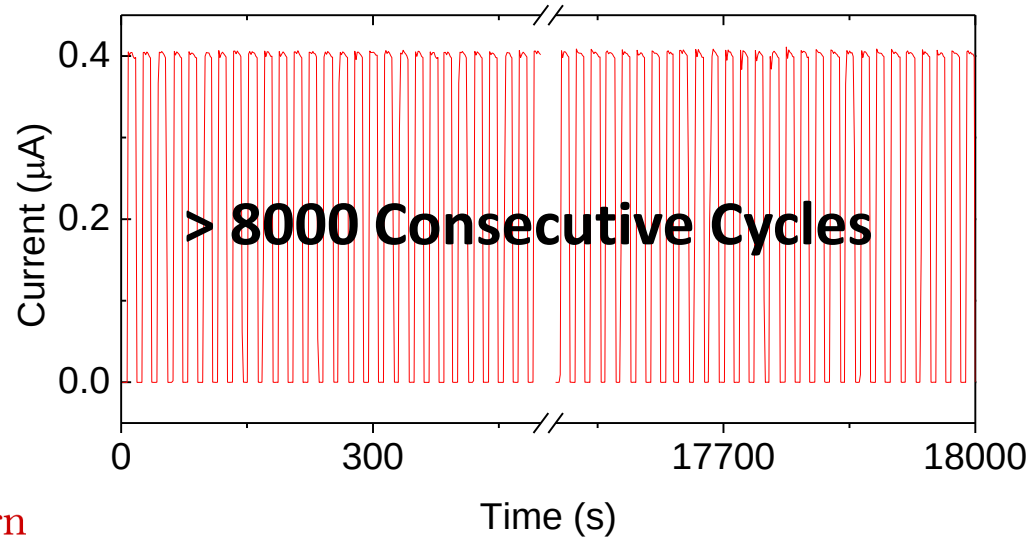
ON-state resistance ~ 3×10^{3} Ω

ON/OFF conductance ratio **> 1×10^{12}**

Sub-threshold leakage current measurement



PMP response to chopped IR radiation:



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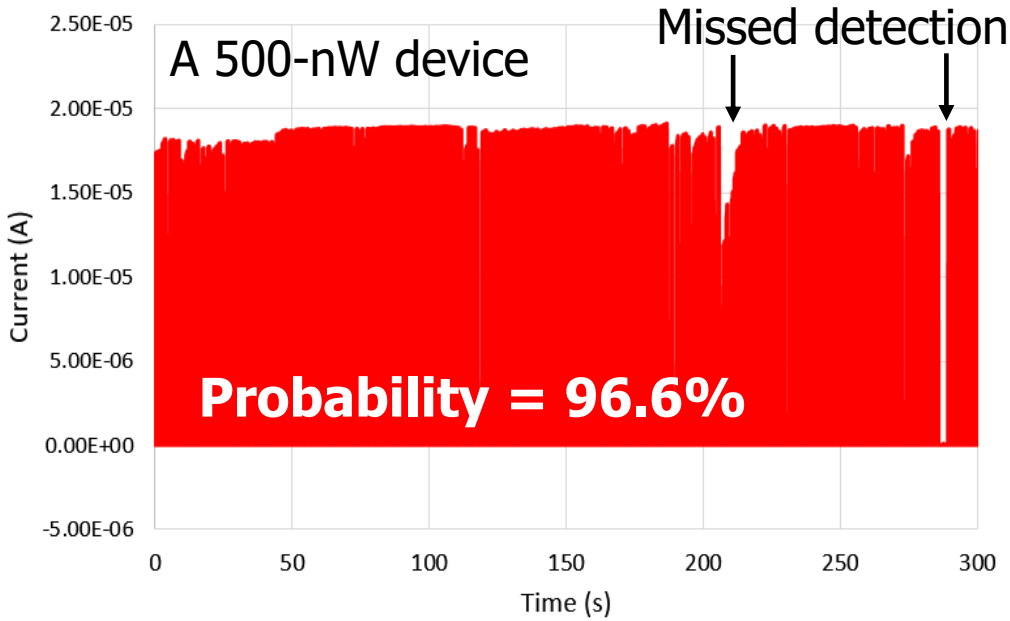
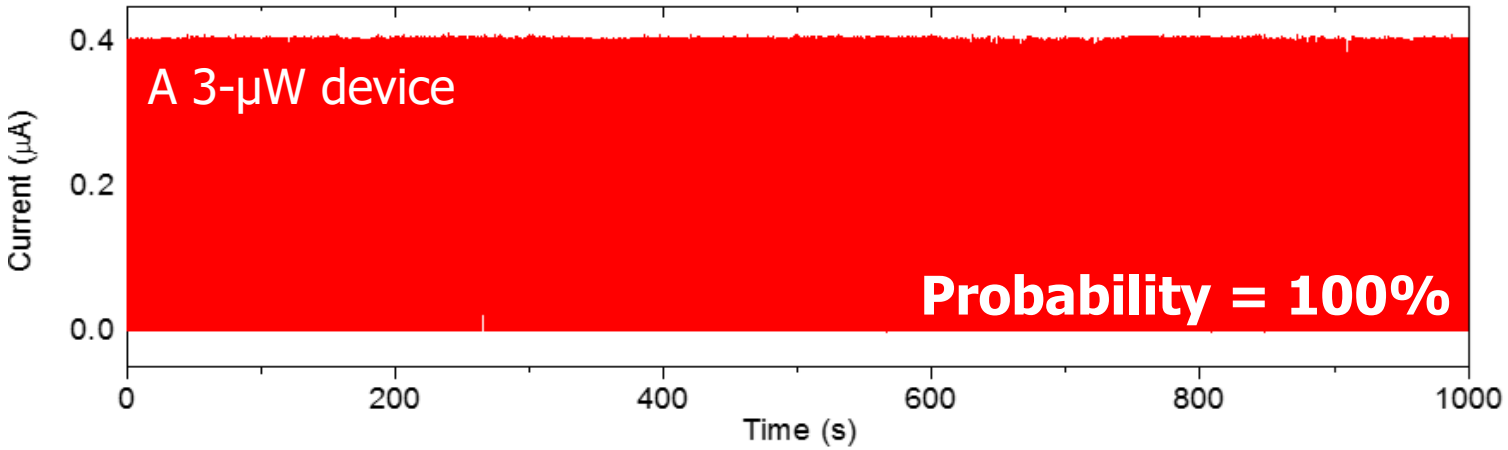
Zero Standby Power Consumption

- **Zero False Alarm Rate (to above-threshold out-of-band radiation)**

  PMPs only turn ON at the design-defined IR spectral band with absorbed power above threshold, and remain OFF otherwise.

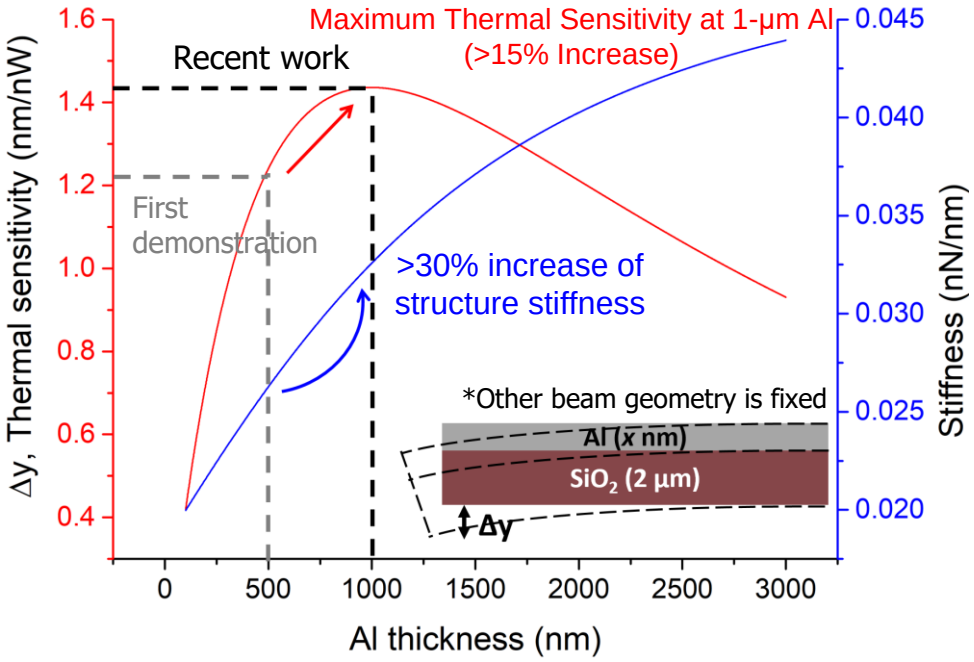
- **Probability of Detection > 95%**



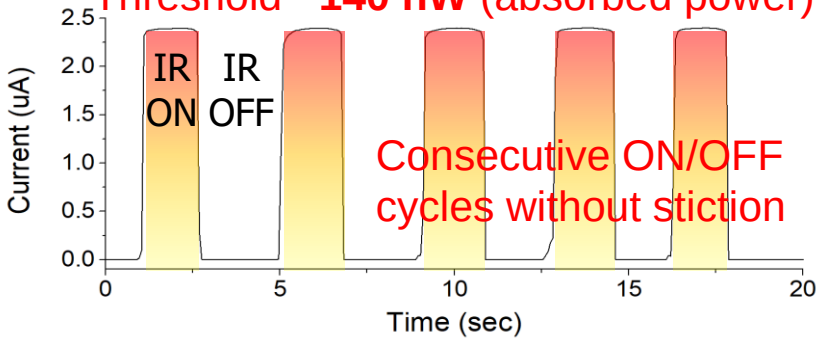


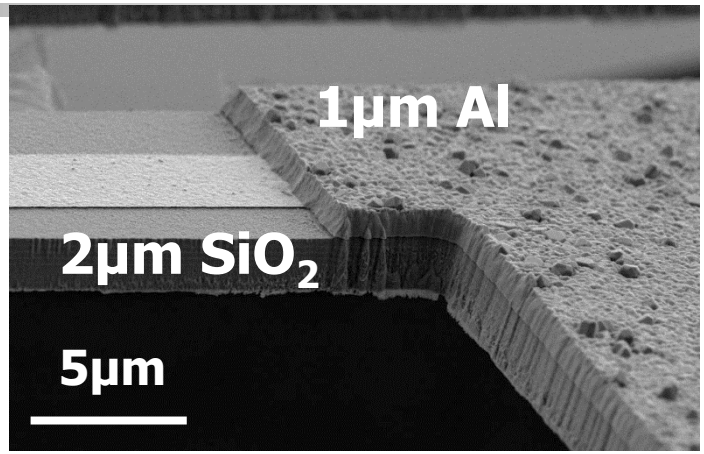
Threshold Scaling by Structural Optimization

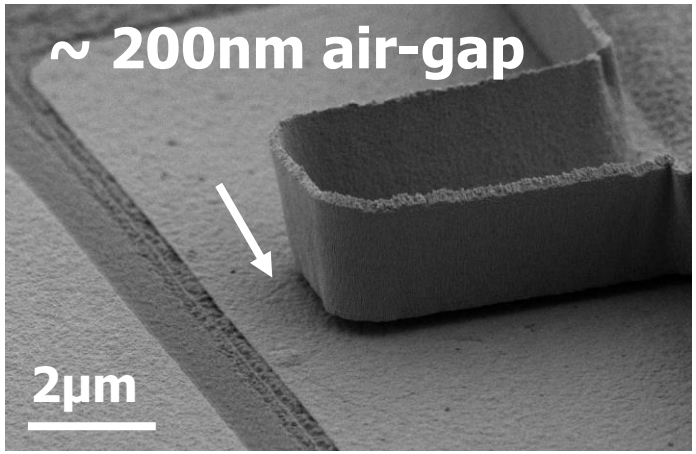
- Increase the thermal sensitivity while maintaining a high stiffness
- Scale the contact gap



Threshold **~140 nW** (absorbed power)







S. Kang, S. Calisgan, Z. Qian, V. Rajaram, N. McGruer and M. Rinaldi, "Broadband Long-Wavelength Infrared Micromechanical Photoswitch for Zero-Power Human Detection", Hilton Head Workshop 2018: A Solid-State Sensors, Actuators and Microsystems Workshop, Hilton Head Island, June 3-7, 2018

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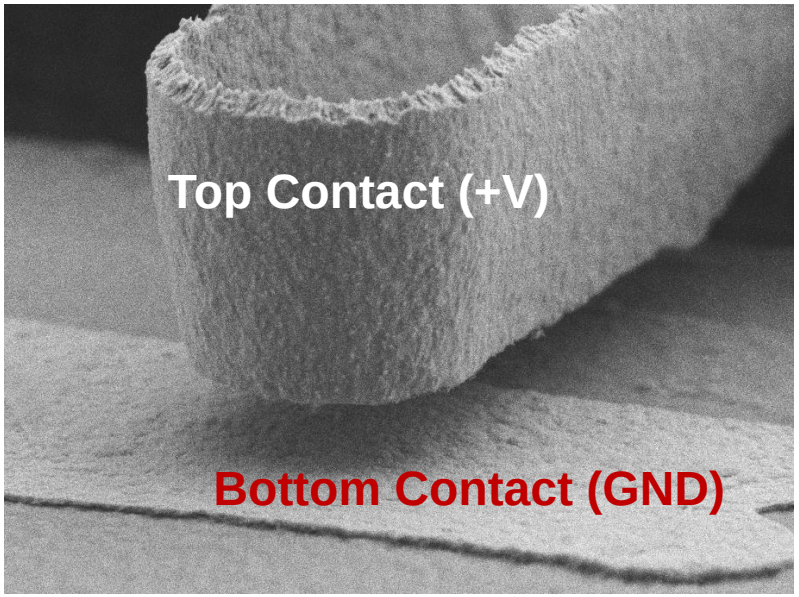
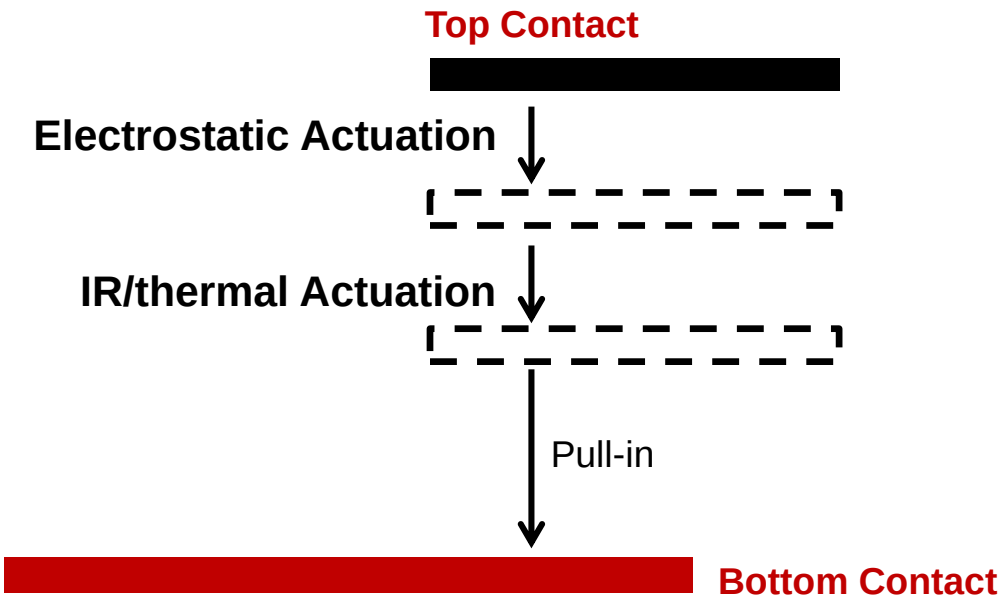
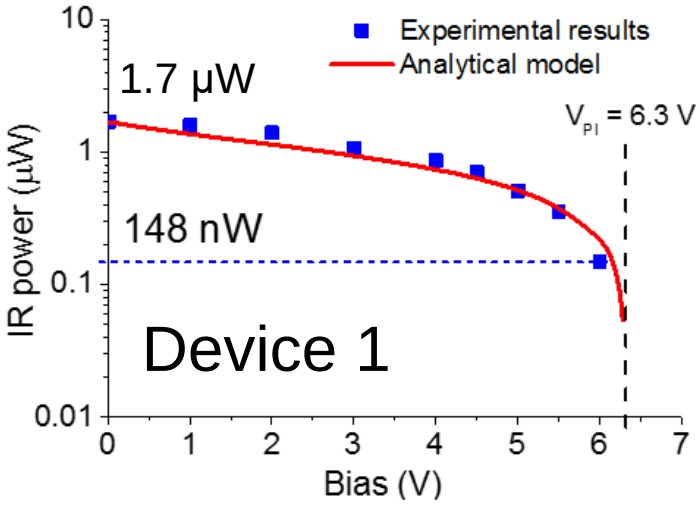
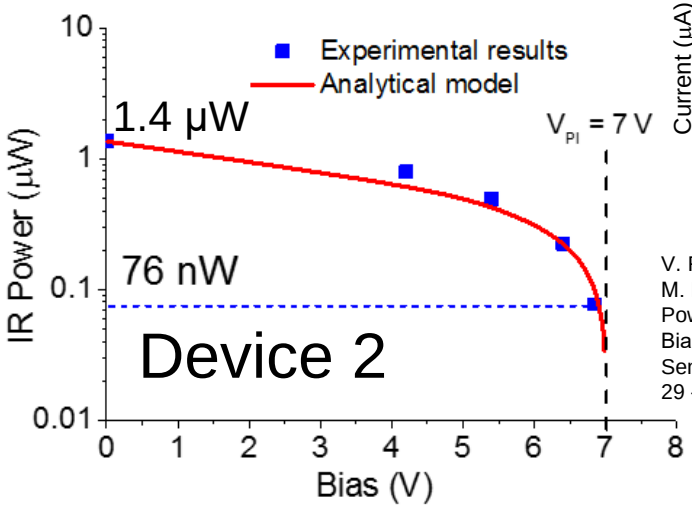
Threshold Scaling with Voltage Bias

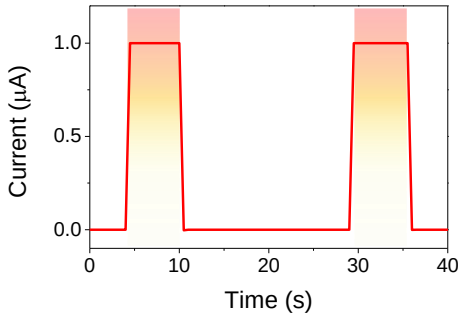




Over 1 order of magnitude improved threshold!







V. Rajaram, Z. Qian, S. Kang, N. McGruer and M. Rinaldi, “Threshold Scaling of Near-Zero Power Micromechanical Photoswitches Using Bias Voltage”, Proceedings of the IEEE Sensors 2017, Glasgow, Scotland UK, October 29 – November 1, 2017, pp. 1-3

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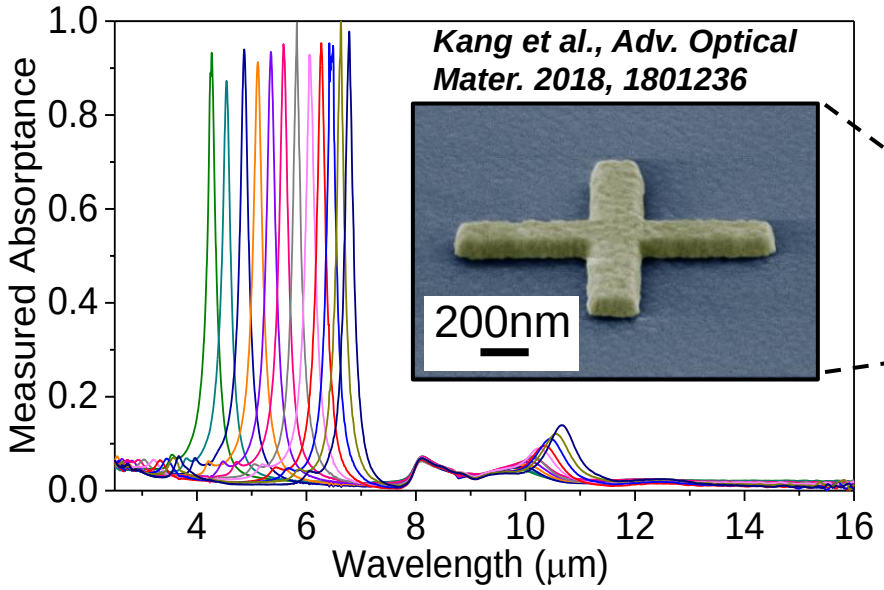
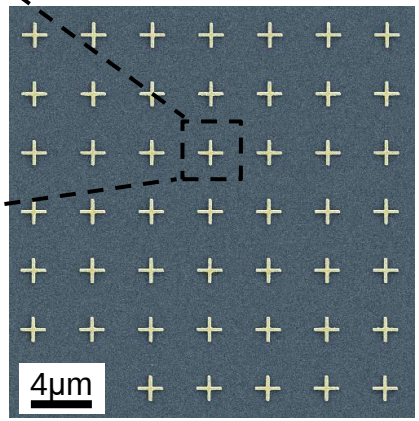
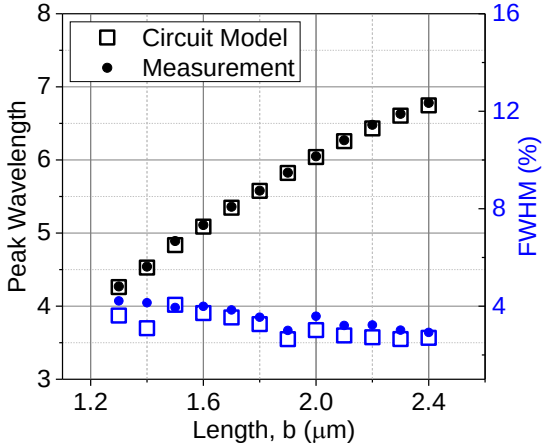
High Spectral Resolution Plasmonic Absorbers

Experimental demonstration of metal-insulator-metal plasmonic IR absorbers

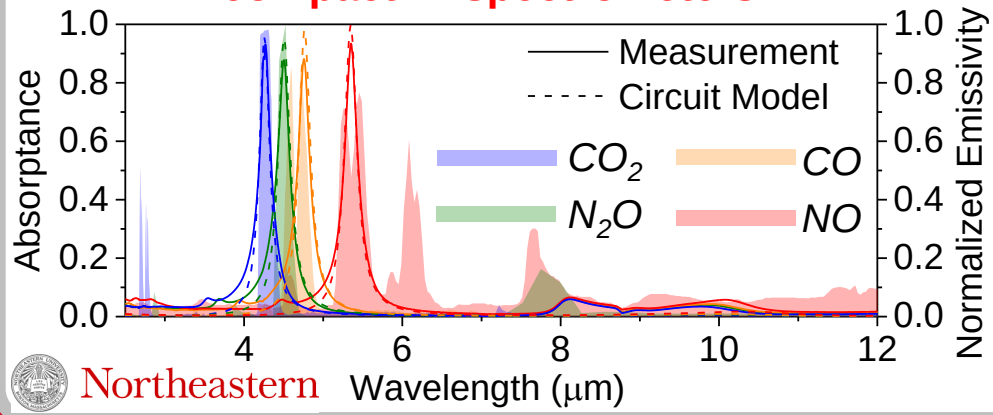


- **Lithographic tuning** of peak absorption wavelengths
- Near-unity absorption (**η>99.7%**)
- High spectral selectivity (**FWHM<180nm**)
- **Polarization and angle insensitivity**

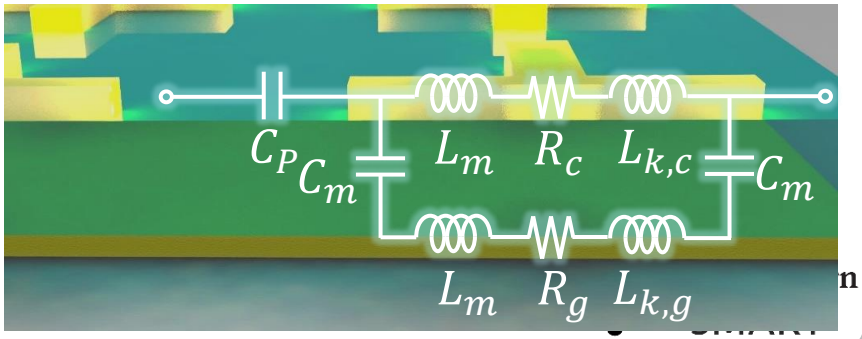




Ideal candidates for compact IR spectrometers

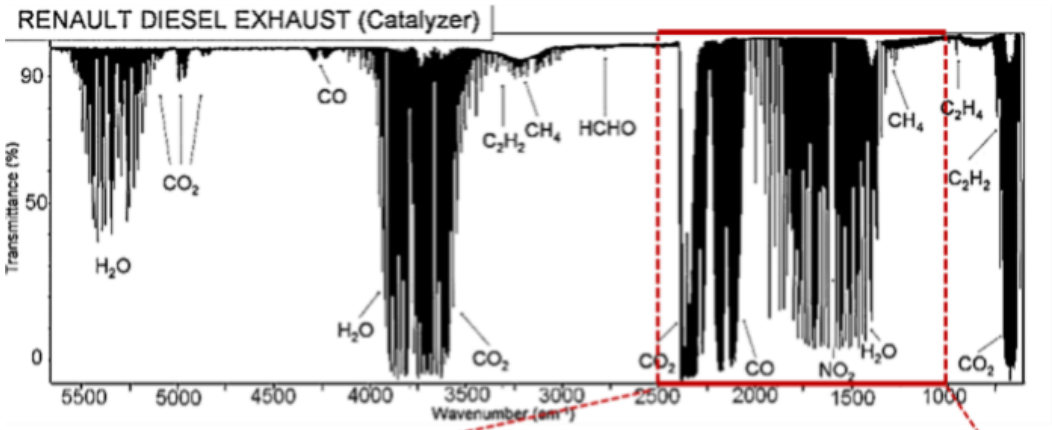


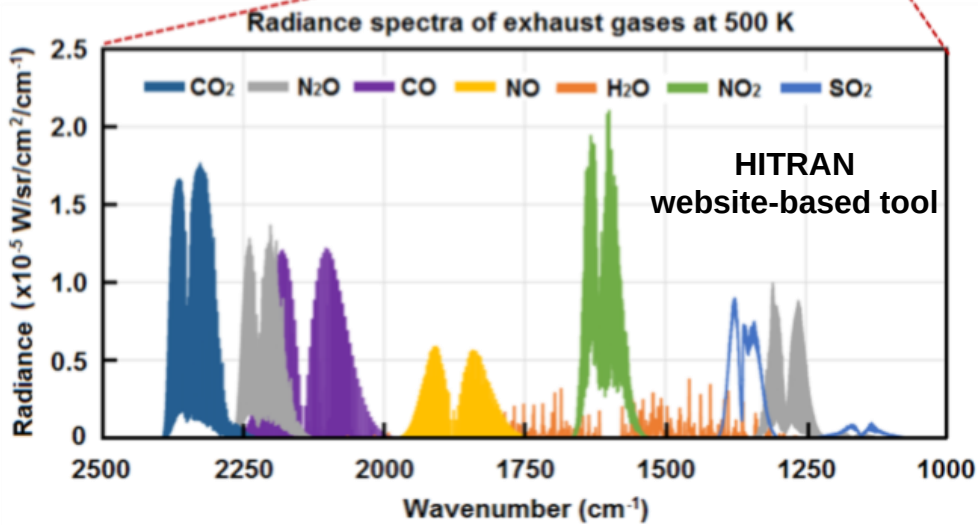
Geometric dimensions **optimized via modified analytical circuit model**



Plasmonic Microelectromechanical Infrared Digitizer

IR spectroscopy based standoff chemical detection

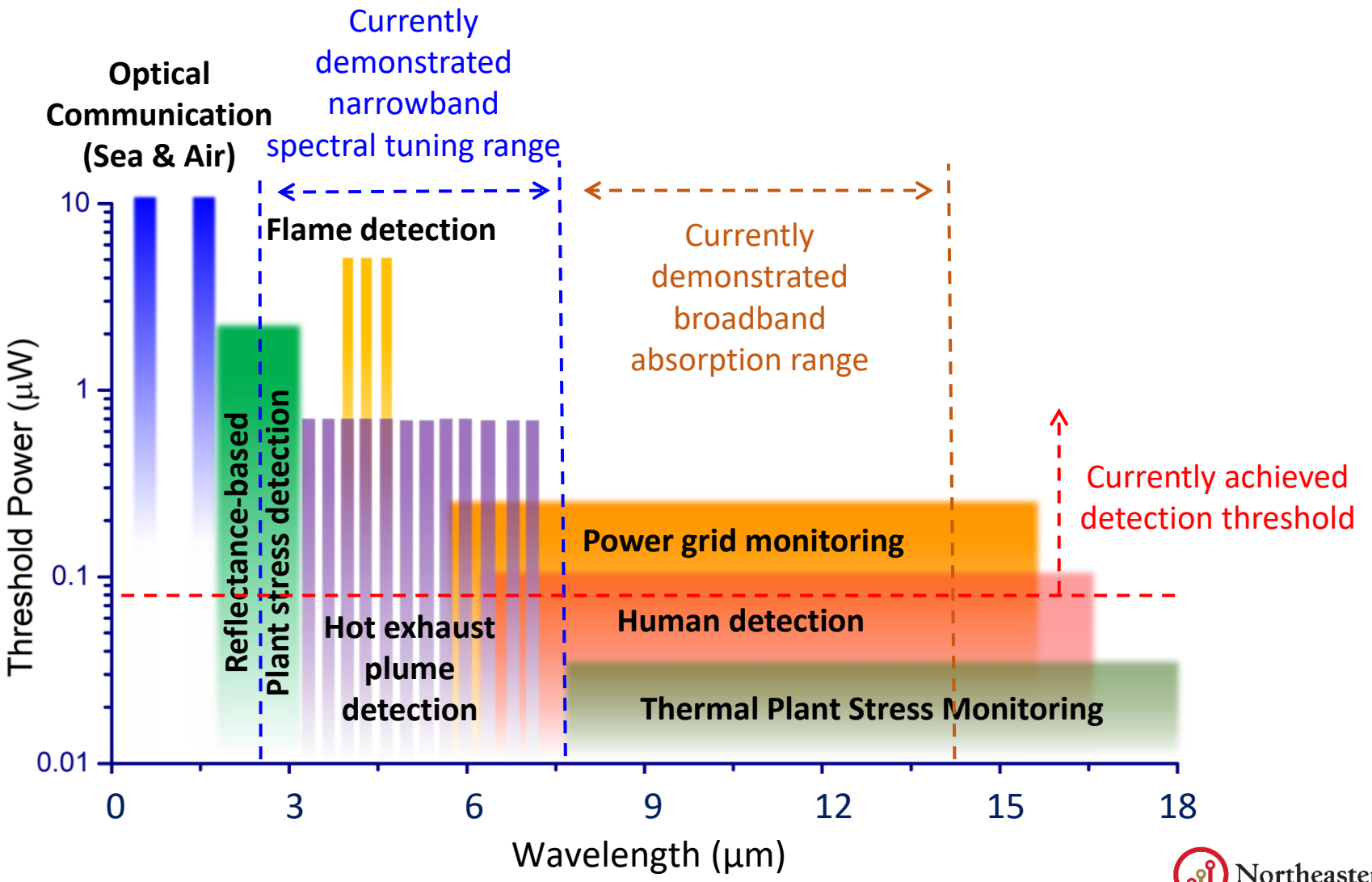




- Engines using gasoline or diesel as fuels produce: ***CO_2, CO, NO_x, H_2O, SO_x in a localized position***
- These gases have ***sharp emission peaks*** in the IR (***4-10 μm***)
- The emission spectrum of these heated gas mixture act as a ***specific signature of a fuel-burning vehicle***

HITRAN is worldwide standard for simulating radiance from the microwave through ultraviolet region of the spectrum

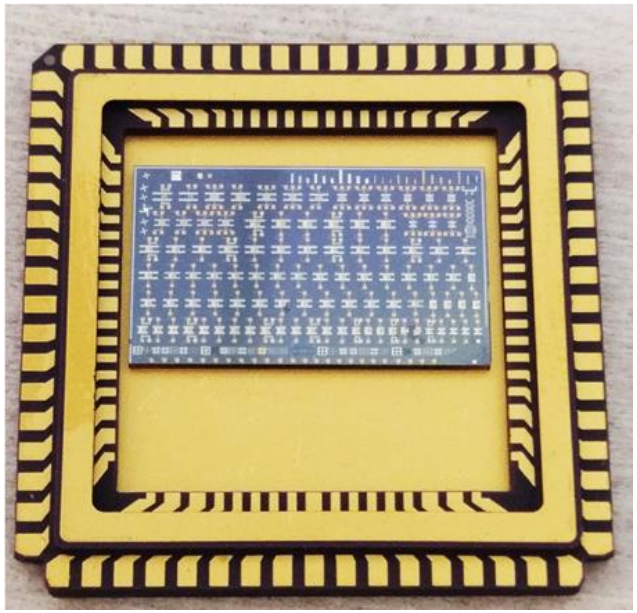
Application Space



Vacuum-packaged PMPs for System Integration

<1 mTorr pressure after >3 months

Ceramic LCC package

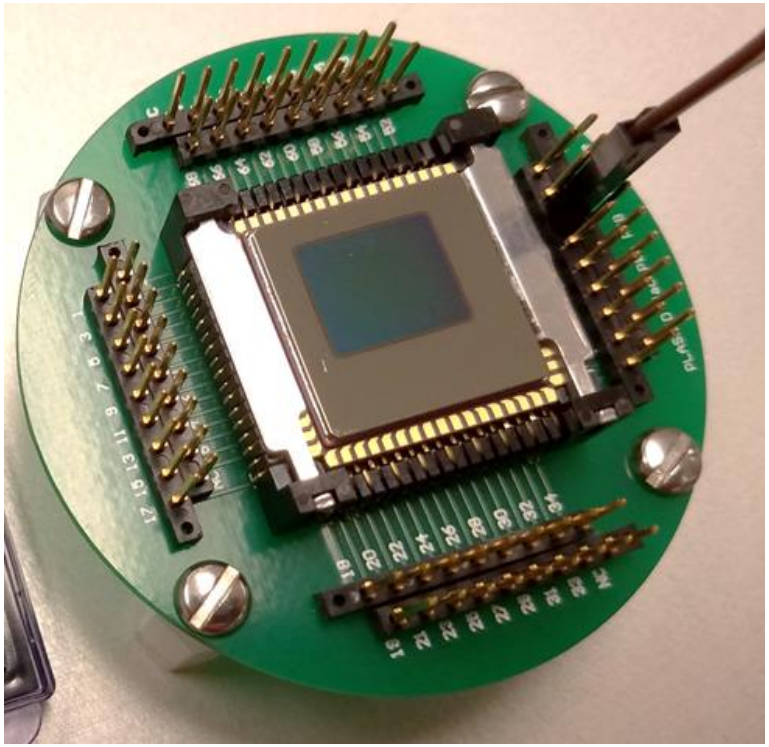


Released chip inside package

175 ° C max. process temperature

Packaging by INO, Canada

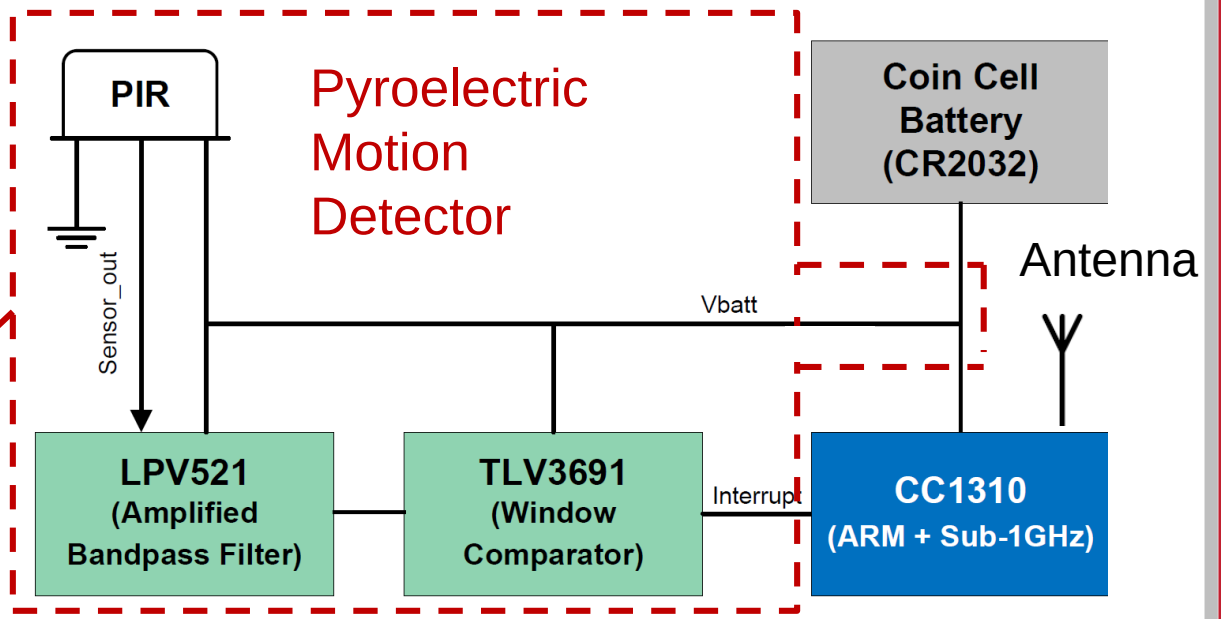
Window: AR-coated Germanium

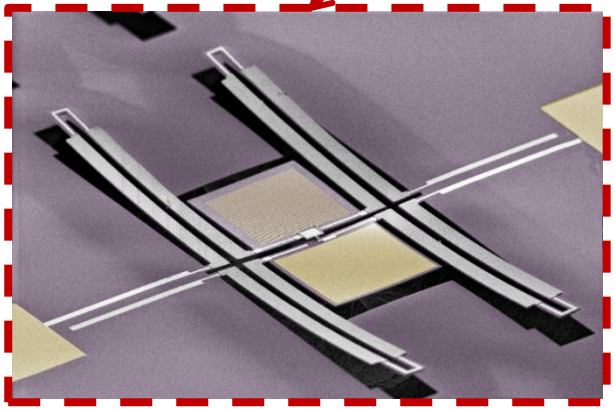


Package mounted on PCB

Near-Zero Power Wireless IR Sensor Node

Texas Instruments PIR sensor with sub -1GHz transceiver



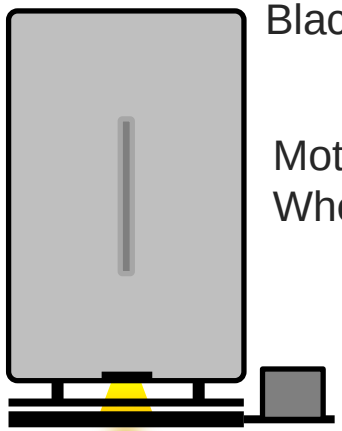


CIRCUIT PATH	SUPPLY CURRENT (IDLE)	
	NOMINAL	MEASURED
Sensor	600 nA	594 nA
Comparators ×2	150 nA	150 nA
Divider	50 nA	50 nA
Opamp1	374 nA	360 nA
Opamp2	409 nA	380 nA
CC1310	100 nA	120 nA
Total	**1.683 µA**	**1.654 µA**

Idle current is reduced to near-zero

V. Rajaram, Z. Qian, S. Kang, and M. Rinaldi, "MEMS-Based Near-Zero Power Infrared Wireless Sensor Node", Proceedings of the 31st IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2018), Belfast, UK, 21-25 January 2018, pp.17-20

Zero Power Wireless IR Sensor Node



Blackbody Source

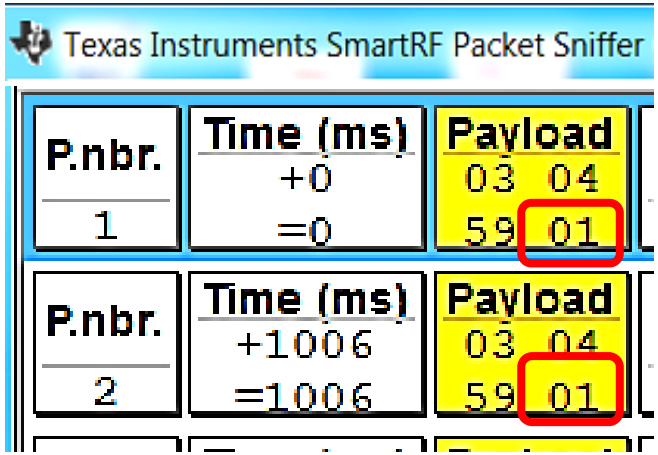
Motorized Filter Wheel

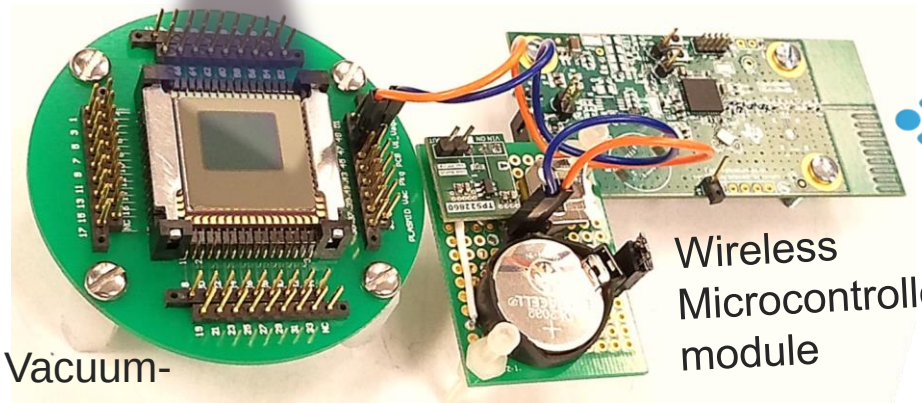
Chopper

Program:

```
while(1) {
  transmit "01";
  delay (1000ms);
}
```

Computer Display



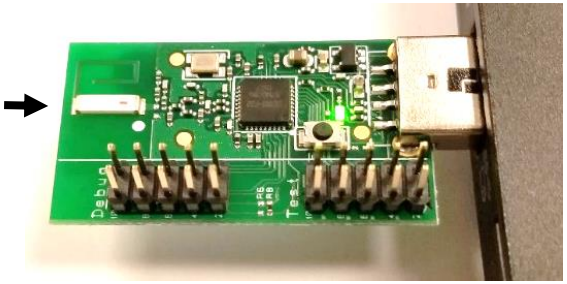


Vacuum-packaged PMP

Load-switch & battery unit

Wireless Microcontroller Tx module

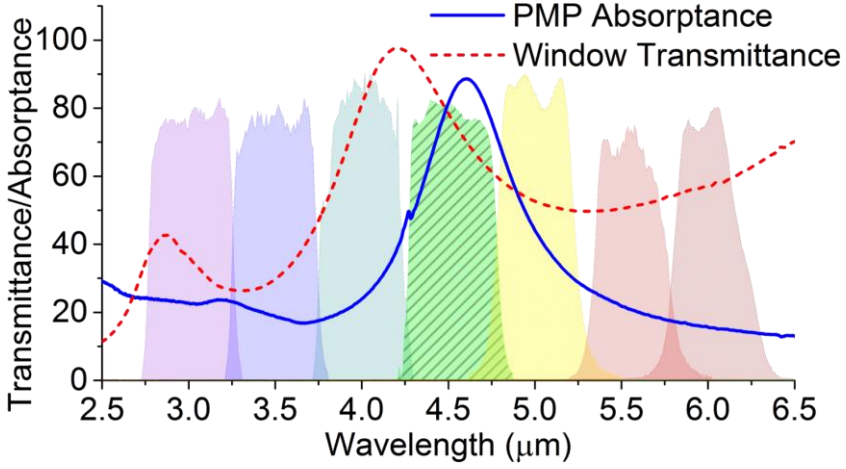
~30 ft

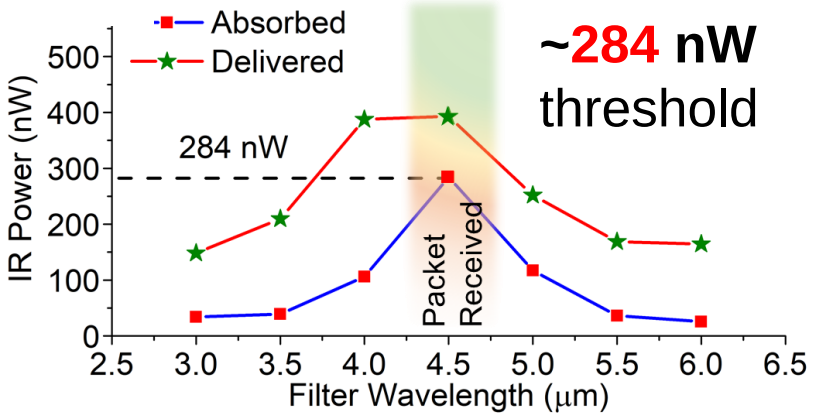


USB Receiver module

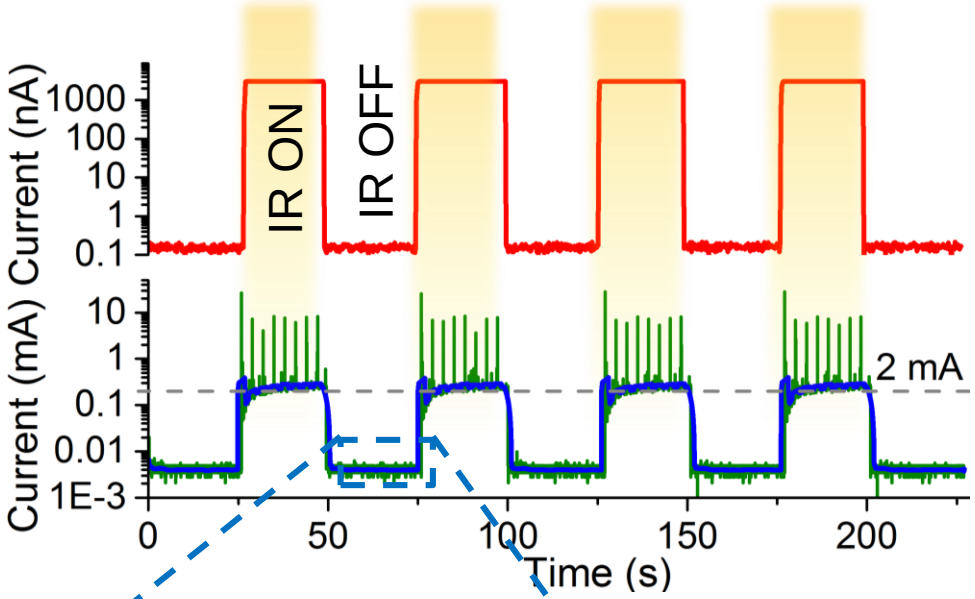
V. Rajaram, Z. Qian, S. Kang, and M. Rinaldi, "MEMS-Based Near-Zero Power Infrared Wireless Sensor Node", Proceedings of the 31st IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2018), Belfast, UK, 21-25 January 2018, pp.17-20

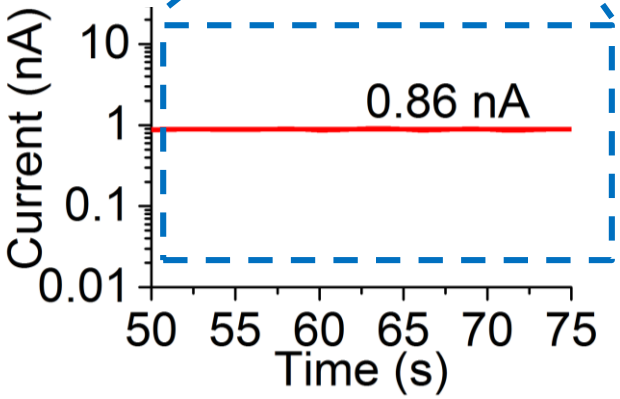
Zero Power Wireless IR Sensor Node





~284 nW threshold





~2.6 nW standby power consumption

V. Rajaram, Z. Qian, S. Kang, and M. Rinaldi, "MEMS-Based Near-Zero Power Infrared Wireless Sensor Node", Proceedings of the 31st IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2018), Belfast, UK, 21-25 January 2018, pp.17-20

Battery-less IR Sensor Tags

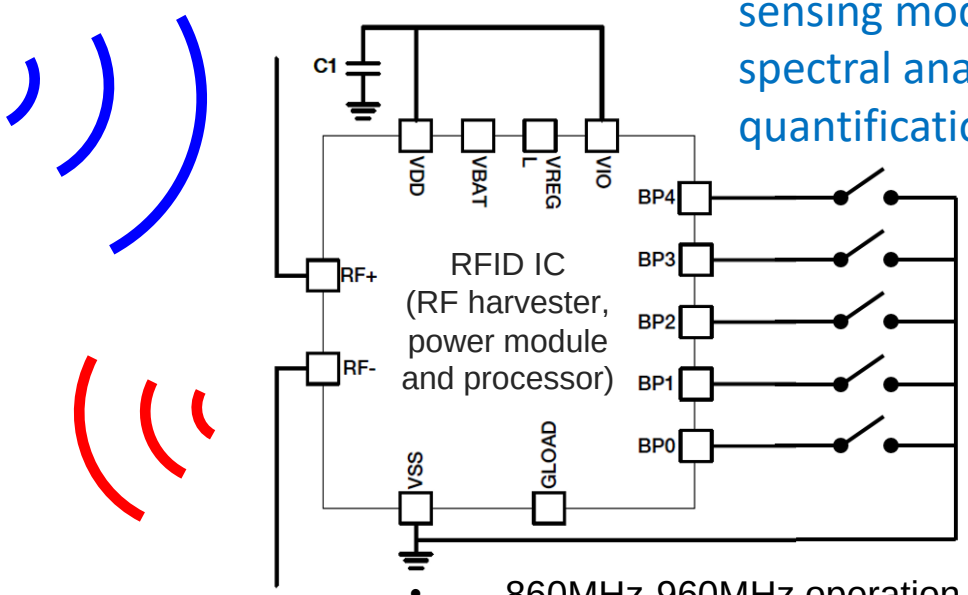
The zero-power and abrupt switching properties enable seamless integration with COTS RFID tags

Battery free: non hazardous and low ecological impact

Multi-channel enables complex sensing modalities such as spectral analysis and finer quantification of IR intensity.

Interrogation signal from a reader

Backscatter signal from the tag indicating the status of the switches



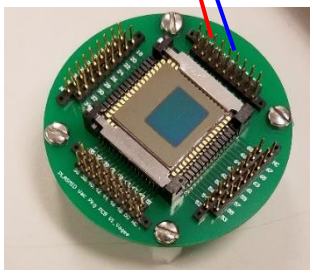
Farsens EVAL01-X5-R

- 860MHz-960MHz operation frequency
- Support standard protocols (EPC Gen 2)
- Read range @ 2W ERP: 5 meters
- Non-volatile memory

V. Rajaram, Z. Qian, S. Kang, S. Calisgan, N. McGruer and M. Rinaldi, “MEMS-Based Battery-less RFID Infrared Sensor Tag With Memory Function”, IEEE MEMS (MEMS 2019), Seoul, Korea, January 27-31, 2019, in press.

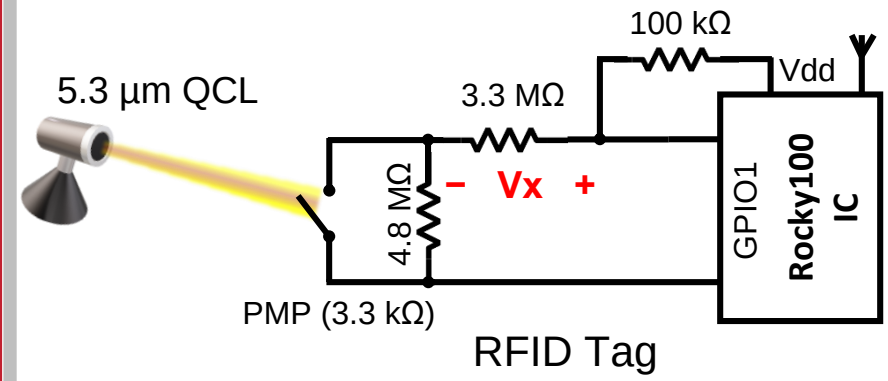
Battery-less IR Sensor Tags

- Sensor node comprises a RFID IC in “switch monitor” mode whose General purpose I/O register changes based on the state of a connected switch
- A USB RFID reader is used to interrogate the sensor node IC to read data in the GPIO register
- The data returned from the register is displayed on PC. Data is read when (a) IR is OFF and (b) IR is ON. As Expected, the data reflects a change in one bit of the register (001F to 001E indicating switch OFF to ON).



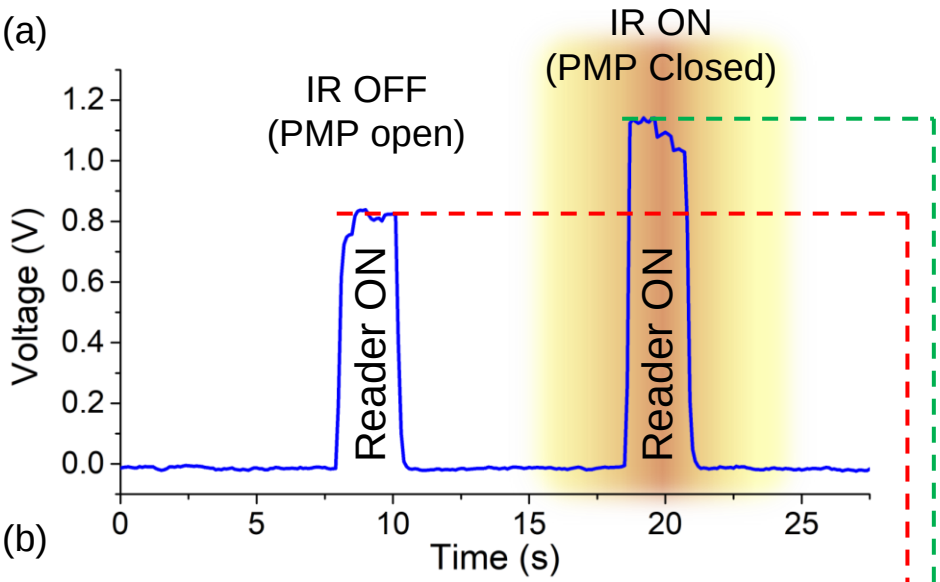
Vacuum-packaged PMP

RFID Reader to PC



RFID Tag

Measurement of Vx on RFID tag

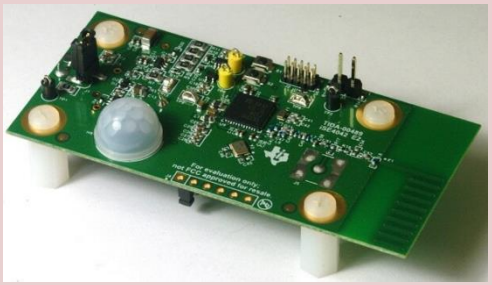
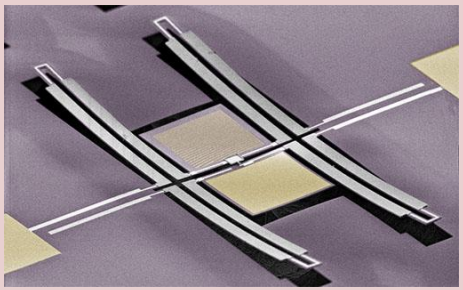


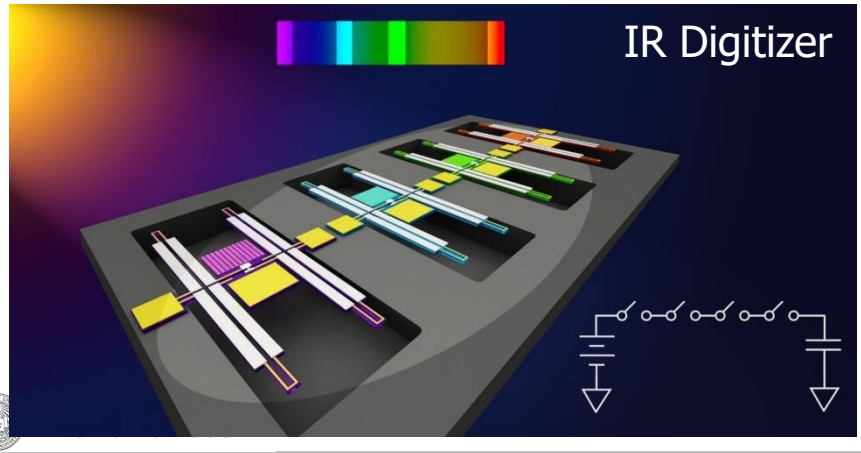
#	EPC	Data	TimeStamp(msec)	RSSI(dBm)	ReadCount
1	000000A93C0000000(	00 1F	04:10:15.954 PM	-30	1
2	000000A93C0000000(	00 1E	04:10:23.264 PM	-32	1

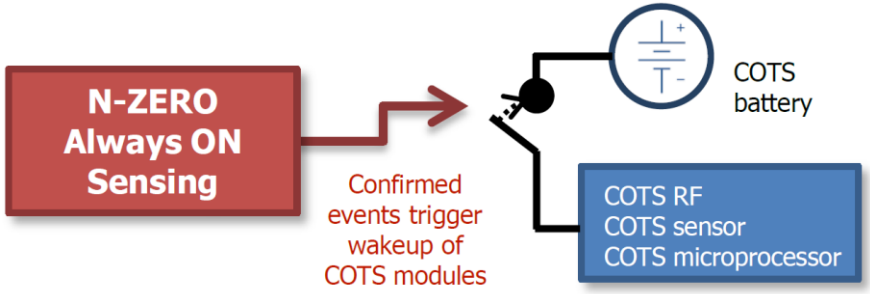
RFID reader software window screenshot (Thingmagic URA)

V. Rajaram, Z. Qian, S. Kang, S. Calisgan, N. McGruer and M. Rinaldi, “MEMS-Based Battery-less RFID Infrared Sensor Tag With Memory Function”, IEEE MEMS (MEMS 2019), Seoul, Korea, January 27-31, 2019, in press.

Comparison to the State-of-the-art

Parameters:	Uncooled IR Photoswitch Technologies	
	 Pyroelectric IR detector with low-power digitizing circuits (e.g. TI motion detector)	 Zero-power PMP
Switching threshold	~ 100s nW	**~ 10s nW**
Power consumption	~ 7 μW	**~ 2.6 nW**
Spectral selectivity	Depend on material properties	Lithographically-defined
IR Signature Detection	NO: Single broad band	**YES: Multiple narrow bands**





Northeastern SMART

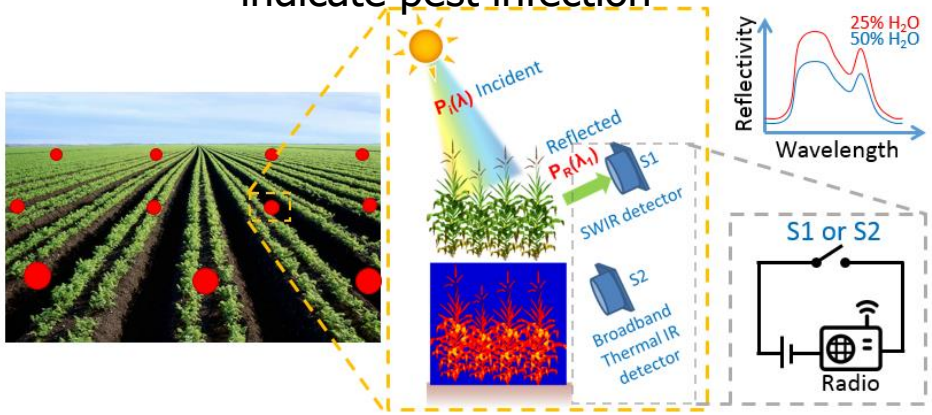
Envisioned Applications

Occupancy Sensing

Indoor people counting system enabled by IR sensor tags

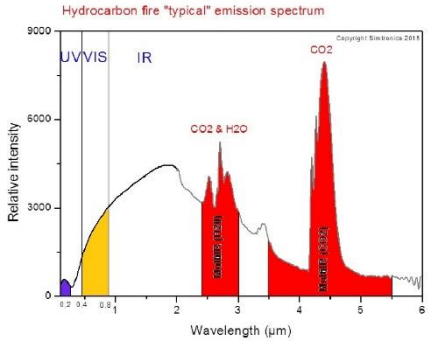
Smart Farms

Reflectivity in SWIR and temperature of leaves indicate their water stress. VOCs indicate pest infection



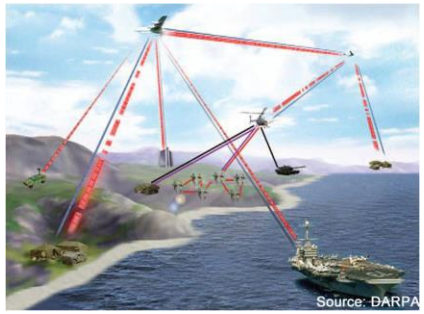
Flame Detection

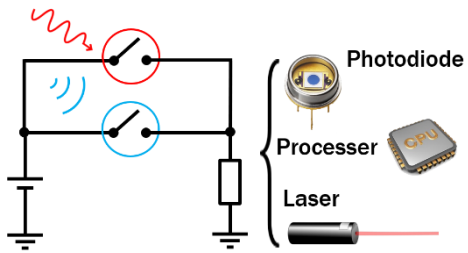
Reduced power consumption leads to lower maintenance cost and ubiquitous sensing



Optical Communication

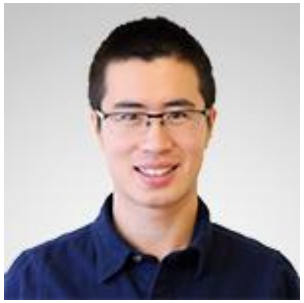
On-demand optical receivers that only consume power when incoming transmission is received.





Team and Acknowledgment

Prof. Matteo Rinaldi



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ALERT
AWARENESS AND LOCALIZATION OF EXPLOSIVES-RELATED THREATS
DHS Center of Excellence

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CAREER Award
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